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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**AUTOMATION OF P-3 SIMULATIONS TO IMPROVE
OPERATOR WORKLOAD**

by

Justin L. Ross

September 2012

Thesis Advisor:
Second Reader:

Chris J. Darken
Curtis Blais

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**AUTOMATION OF P-3 SIMULATIONS TO IMPROVE OPERATOR
WORKLOAD**

Justin L. Ross
Lieutenant, United States Navy
B.S., University of Maryland, 2006

Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN
MODELING, VIRTUAL ENVIRONMENTS, AND SIMULATION (MOVES)**

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**NAVAL POSTGRADUATE SCHOOL
September 2012**

Author: Justin L. Ross

Approved by: Chris J. Darken
Thesis Advisor

Curtis Blais
Second Reader

Chris J. Darken
Chair, MOVES Academic Committee

Peter J. Denning
Chairman, Department of Computer Science

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ABSTRACT

The purpose of this research was to develop a methodology for creating P-3 Aircraft behaviors in the Joint Semi-Automated Forces (JSAF) simulation to help reduce the workload of JSAF terminal operators, which saves money for the Navy by lowering the number of operators required. JSAF is the core simulation engine of the Navy Continuous Training Environment, which is used to connect simulations and live units to conduct Fleet Synthetic Training (FST) exercises. There were three major steps to the methodology of this research. First, a task analysis of P-3 pucksters was conducted by interviewing subject matter experts and observing training exercises. Next, the proper mode of interfacing with JSAF was determined by weighing the pros and cons of several methods. Finally, an adaptive sonobuoy placement behavior was developed and implemented in JSAF. The behavior was successfully implemented in a local JSAF terminal and preliminary tests showed a significant potential for reducing the workload of JSAF operators. It is recommended that the adaptive sonobuoy behavior be fully developed and implemented in JSAF and this methodology be used to automate further behaviors in JSAF, which will lead to reduced manning requirements for FST exercises.

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LIST OF ACRONYMS AND ABBREVIATIONS

AGC	Automatic Gain Control
AIP	Anti-Surface Warfare Improvement Program
AOR	Area of Responsibility
ASW	Anti-Submarine Warfare
ATO	Air Tasking Order
BLA	Basic Level Action
BMD	Ballistic Missile Defense
BT	Bathymograph
C2	Command and Control
CAD	Cartridge Actuated Device
CFS	Command Function Select
CMDS	Countermeasures Dispensing System
CO	Calibrated Omni
COP	Common Operational Picture
CSO	Constant Shallow Omni
CTDB	Compact Terrain Database
CTF	Combined Task Force
DICASS	Directional Command Activated Sonobuoy System
DIFAR	Directional Frequency Analysis and Recording
DLC	Data Link Communications
DoD	Department of Defense
EFS	Electronic Function Select
ESM	Electronic Support Measures
EWO	Electronic Warfare Operator
FE	Flight Engineer
FST	Fleet Synthetic Training
GBE	Group Behavior Engine
GCC	Geocentric Coordinates
GCS	Global Coordinate System
GUI	Graphical User Interface

HLA	High Level Architecture
IFT	In-Flight Technician
IRDS	Infrared Detecting Set
ISR	Intelligence, Surveillance and Reconnaissance
JSAF	Joint Semi-Automated Forces
JTEN	Joint Training and Experimentation Network
LNO	Liaison Officer
LOFAR	Low-Frequency Analysis and Recording
M&S	Modeling and Simulation
MAD	Magnetic Anomaly Detection
MMA	Multi-Mission Aircraft
MOVES	Modeling, Virtual Environments, and Simulation
MPA	Maritime Patrol Aircraft
MWS	Missile-Warning Set
NAV/COMM	Navigator/Communicator
NCTE	Navy Continuous Training Environment
NFO	Naval Flight Officer
NPS	Naval Postgraduate School
NWDC	Naval Warfare Development Command
PVD	Plan View Display
RF	Radio Frequency
RTI	Run-Time Infrastructure
SASP	Single Advanced Signal Processor
SCCD	Sea Combat Commanders Display
SME	Subject Matter Expert
SPL	Sound Pressure Level
SUW	Anti-Surface Warfare
TACCO	Tactical Coordinator
VoIP	Voice over Internet Protocol

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I. INTRODUCTION

Recent budget cuts across the board in the Department of Defense (DoD) have forced the Navy to consider more cost-efficient methods for training the fleet than those currently employed. The most realistic training involves the coordination of several platforms in their natural operating environment. This type of training is expensive due to the expenditure of fuel and consumables while the ships are underway. For example, one day's worth of fuel for a surface combatant costs at least \$40,000 (Yardley et al., 2008). One way to reduce the cost of training and still maintain a sufficient level of realism and training value is through the use of simulations. Simulations can range in complexity from a single-person laptop program to a complex networked virtual environment.

The use of simulations for training also has its own set of problems. Many simulations have simulated entities with varying levels of automated behavior built in. In many cases a human operator will have to provide some control of the simulated entities to ensure their behaviors accurately represent the actions of real-world entities. There are some cases where the operator providing the simulation controls is not specifically trained in the tactics or behaviors of the entities they are controlling or they may have limited training and experience with the simulation system being operated. The challenge for any training simulation is to minimize the amount of human input required to operate the system while still maintaining realistic behaviors.

One particular area where simulation is used extensively is Fleet Synthetic Training (FST). The Navy Continuous Training Environment (NCTE) is the system used to support FST events, among other uses. NCTE is a vital part of fleet training, but it is becoming more expensive and operationally infeasible to conduct large-scale fleet exercises. Joint Semi-Automated Forces (JSAF) is the primary simulation engine incorporated into NCTE, although a given exercise consists of a large federation of virtual and constructive simulations and crews participating from combat stations aboard participating vessels.

JSAF can represent military operations at the entity level and can communicate with real-world C4I systems. An FST event requires several support staff to manage and operate JSAF terminals for simulating the entities needed for training. Each JSAF terminal operator (“puckster”) adds cost to the training exercise. In a recent exercise, 17 personnel were used to simulate P-3C Orion Multi-Mission Aircraft (MMA) operations alone, with the possibility of needing more in some circumstances.

To minimize the task demand on the P-3 pucksters and ultimately reduce the number required for FST exercises while providing accurate and realistic behaviors, the following research questions must be answered: 1) What are the cognitive processes and physical actions a simulation operator must complete when controlling P-3 behaviors in the NCTE? 2) What is the most efficient input/output method for communicating between automation software and the P-3 simulation? and 3) Can the task demand of P-3 simulation operators be reduced enough to lower the number of personnel required to run the simulation by providing software that automates some of the tasks that are normally performed by the operators? The first two questions are secondary research questions, which will inform the methods for answering the third question, which is the primary research question for this study.

To reduce the number of pucksters required to simulate P-3 behaviors is the ultimate goal of this research. To accomplish this goal, an analysis of JSAF terminal operators responsible for simulating P-3 operations was conducted to determine the behaviors that should be automated to give the most savings in workload. Next, the best method of input and output with the JSAF software was determined, followed by the development of software to automate P-3 behaviors. An adaptive sonobuoy placement behavior was developed that shows potential for a significant reduction in operator workload. This research provides a methodology for developing automated behaviors in JSAF to reduce the task demand on P-3 pucksters and lead to a reduction in the number of operators required for FST exercises, thereby reducing cost and manpower requirements for the Navy. This methodology can be applied to develop further behaviors to help reduce the number of operators required to simulate other types of platforms in JSAF to help NWDC meet their budget demands.

II. BACKGROUND

A. FLEET SYNTHETIC TRAINING

The Fleet Synthetic Training system is a live, virtual, and constructive simulation system used for Navy, Joint and Partner Nation training. It consists of simulated entities, personnel operating simulated equipment in various trainers, and operation of actual shipboard equipment that is linked to the virtual environment. FST is based on the concept of distributed “integrated training,” which allows units to connect from pier side or their home base with the training audience connected across their Areas of Responsibility (AORs) (Wentz, 2010).

An example of how actual units, simulated entities and headquarters might be set up for a typical FST exercise is shown in Figure 1. Many levels of training can be accommodated with FST. Training can be at the unit, multi-unit, staff, multi-service, bilateral, or multi-national level (Wentz, 2010). A series of training events can provide warfare proficiency training, interoperability training, operational training, mission rehearsal training, and joint operability training (Jay, 2008). FST can accommodate training for at least a portion of their mission sets for nearly all warfare areas required of Navy, joint and coalition participants (Jay, 2008).

Several simulation and network architectures are used to accomplish this complicated training task. The primary systems used for FST are the Joint Training and Experimentation Network (JTEN) and the Navy Continuous Training Environment (NCTE). The JTEN provides network connectivity between joint and coalition forces and the NCTE provides the Navy’s network portal to the network of joint training simulations.

The advantage of FST is that it optimizes the mix of live and synthetic training, which allows for adequate live training while leveraging the benefits of synthetic training to the maximum extent possible (Jay, 2008). It is also the primary means to integrate geographically-dispersed naval, joint and coalition forces by utilizing shore-based and

ship-embedded simulation systems linked by distributed global networks (Jay, 2008). Studies have shown that fleet readiness increases as restrictions to training decrease and as more training technology becomes available (Wentz, 2010). FST uses cutting edge technology to provide for a broader scope of training, which raises the readiness level of the fleet while minimizing the impact on the Navy's budget.

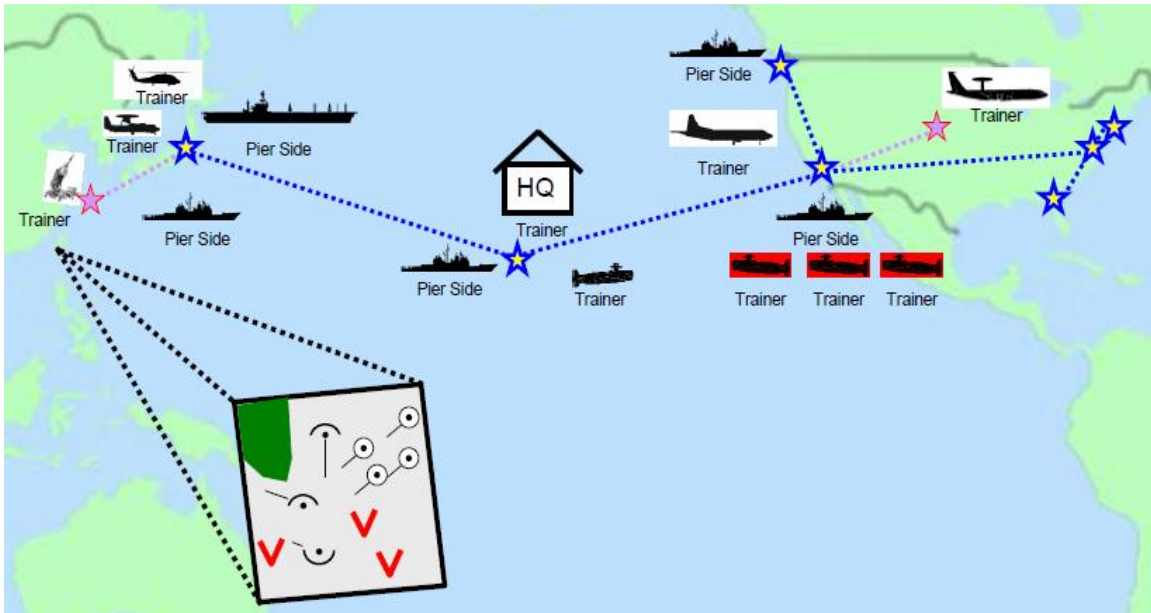


Figure 1. Fleet Synthetic Training Diagram (From Wentz, 2010)

1. NCTE

The Navy Continuous Training Environment (NCTE) is a robust high-speed, switched IP network of simulation systems operated by Naval Warfare Development Command (NWDC). The network is designed to provide reliable bandwidth for 24/7 sustained training operations. As shown in Figure 2, the NCTE links geographically-separated training centers, operational commands, and coalition partners and incorporates them into a common synthetic environment.

NCTE is a global-network infrastructure and integrated-communications enterprise designed and maintained by the NWDC modeling and simulation directorate

(Quick, 2011). It is capable of providing a complete simulation environment encompassing the complete battle space with all of its dynamic systems, physical models, and environmental factors (Quick, 2011). NCTE also delivers real-time voice and command and control among distributed participants. It has the ability to host multiple training, exercise, experimentation, wargaming or concept development events simultaneously. Events may be sponsored by a number of organizations, including (but not limited to) the Chief of Naval Operations, U.S. Fleet Forces Command, and the Office of Naval Research (Quick, 2011).

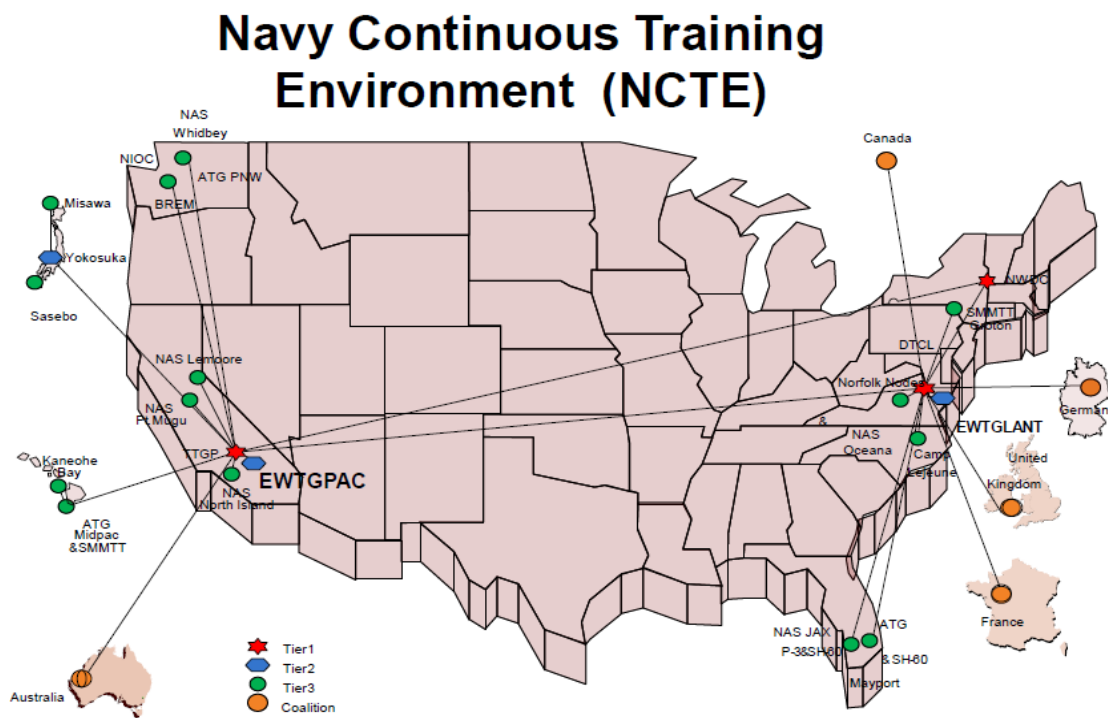


Figure 2. NCTE Connectivity Diagram (From Wentz, 2010)

One example of the value of the NCTE can be seen in training for Ballistic Missile Defense (BMD). There is no capability to train for BMD in a live environment. By using the NCTE and accompanying simulations the threat of ballistic missiles can be realistically simulated, allowing the crews of platforms and the command element to train on BMD scenarios using their actual equipment, which is connected to a virtual

environment. There are other instances of extreme situations that cannot be safely emulated with live training that can be modeled in the NCTE, making it a vital part of the fleet training program.

The NCTE is the world's largest and most reliable simulation network (Quick, 2011). The network has connections with all fleet concentration areas, all naval air stations with air simulators, and a growing number of multi-national coalition forces (Quick, 2011). The relevance of synthetic training is increasing each year due to the shrinking DoD budget. According to NWDC's Modeling and Simulation (M&S) deputy director Darrel Morben, "The requests for exercises and experiments are increasing with more than 350 synthetic events planned for NCTE next year" (Quick, 2011).

2. JSAF

Joint Semi-Automated Forces (JSAF) is the entity level simulation system that is the backbone of the synthetic environment provided by the NCTE. JSAF generates joint-service military, opposition forces, and civilian platforms (vehicles, people, and systems) that operate within and respond to a synthetic environment. It can operate in a stand-alone mode or as part of a suite of simulation systems to provide input to various command and control systems in training, exercise, or experimental settings (Naval Warfare Development Command, 2011).

The core program libraries for JSAF are maintained by NWDC. The JSAF source code has over 1200 libraries and 2 million lines of code. The primary programming language for JSAF is C++ and it operates under a Linux operating system. JSAF is High Level Architecture (HLA) compliant and communicates physical battlefield state and events using the HLA Run-Time Infrastructure (RTI). The JSAF software libraries, which are maintained by NWDC, are tailored to meet the needs of the Navy and joint training communities and are in compliance with the NCTE standards 4.0 (Naval Warfare Development Command, 2011).

a. JSAF Models

JSAF models can represent vehicles, units, life forms and structures and are characterized by three categories of information, which are physical characteristics, performance characteristics, and behaviors. Physical characteristics are necessary for an entity that will have a visual appearance in the simulation. There is a standard set of physical parameters such as width, length, height, draft, collision width, and lethal range. In some cases, if there are components that affect the size of the entity, such as gun turrets, they will be included as part of the entity physical description (Naval Warfare Development Command, 2011). Performance characteristics define the basic capabilities of entities and are defined in reader files containing their parameters. These characteristics include consumption rates, movement capabilities at different speeds and terrains, and damage models. Entity components, such as weapons, sensors, and communications systems are also included in the performance characteristics of an entity. Behaviors are a set of tasks that the operator can assign to an entity platform, which are tailored to the vehicle type and normal mission. The idea for behaviors is that an operator can assign a task, for example “Deploy Sonobuoys,” and the entity will follow standard doctrine to complete the task with minimal input from the operator. The realism and complexity of the behaviors varies among the entity types available in JSAF.

The JSAF models are designed to operate in a synthetic environment that is networked with geographically dispersed simulation centers and training units via the NCTE. The synthetic environment is created by a compact terrain database (CTDB) with terrain that is based on real world mapping containing information such as altitude/depth, soil type, grade, and buildings (Naval Warfare Development Command, 2011). Some terrain features can be “dynamic” and may change based on events occurring in the simulation, such as bombs detonating, or features could temporarily be changed based on operator inputs to the system. JSAF entities are also affected by the weather and ocean conditions in the simulation, which are provided by either JSAF environmental models or real weather/simulated real weather data from other simulation systems or weather systems (Naval Warfare Development Command, 2011).

b. JSAF Displays

There are two primary displays used by the JSAF operator to interact with entities and the simulation environment, the Plan View Display (PVD) and the Sea Combat Commander Display (SCCD). The PVD provides a complete picture of the current simulation for the operator by displaying the “ground truth” of all friendly and enemy force entities in the simulation. The operator may not be able to control all entities visible on the PVD depending on the Command and Control (C2) permissions level of the station. A sample view of the PVD is shown in Figure 3.

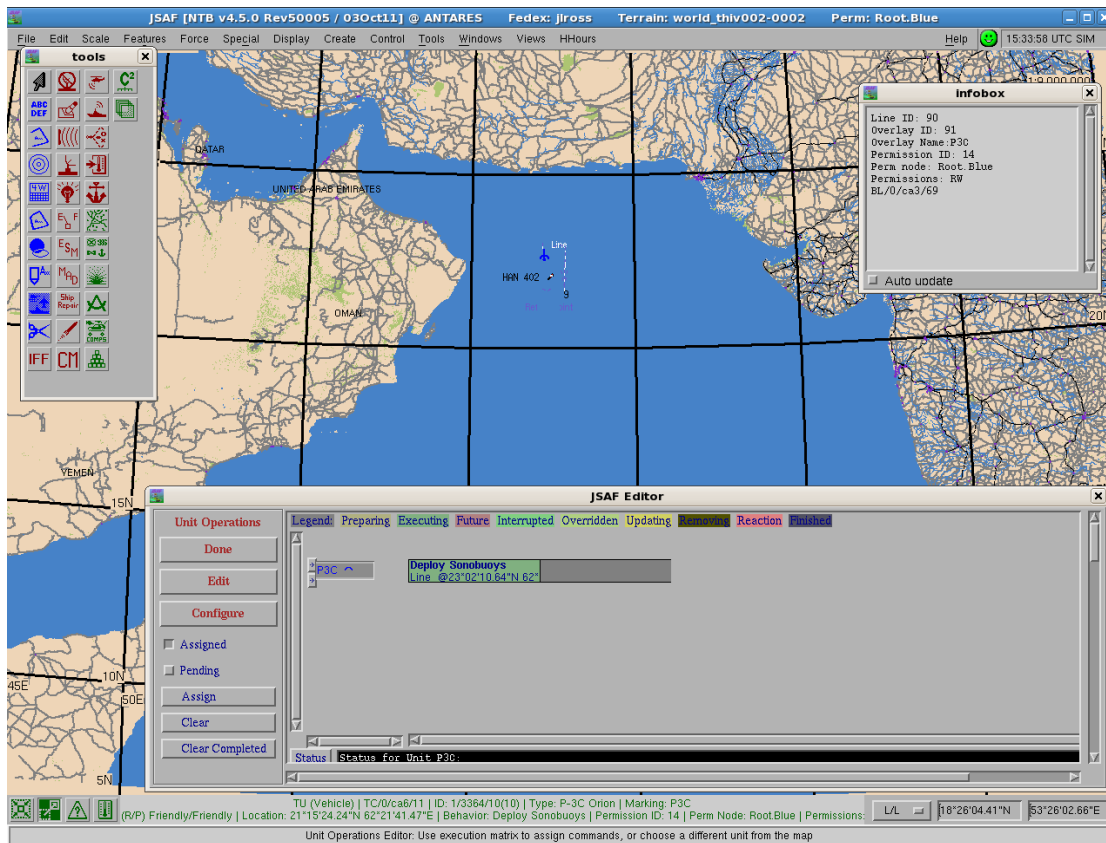


Figure 3. JSAF Plan View Display

The SCCD is the display primarily used by the JSAF operators coordinating with role players in the simulation exercise. The role players, also known as Liaison Officers (LNO), act as entity, group, or task force commanders for the simulated

entities to bridge the gap between the training audience and the JSAF operators. The SCCD only displays entities that are under the control of a particular station as well as the platforms or entities that are held by friendly sensors. The control of entities is determined by the C2 permission group of each station. For example, one station's C2 permission group might be Root.Blue.Air.MPA, which means that the station has control of all blue force Maritime Patrol Aircraft (MPA) platforms. The JSAF developers intend for the SCCD to be the primary display used by JSAF operators since it shows only the information that would be available to a mission commander.

The standard setup for the display on the SCCD has three panels as shown in Figure 4, the geographic map in the center, the platforms panel on the left, and the platform control panel on the right. There is also a menu bar along the top to provide access to display and simulation control functions.

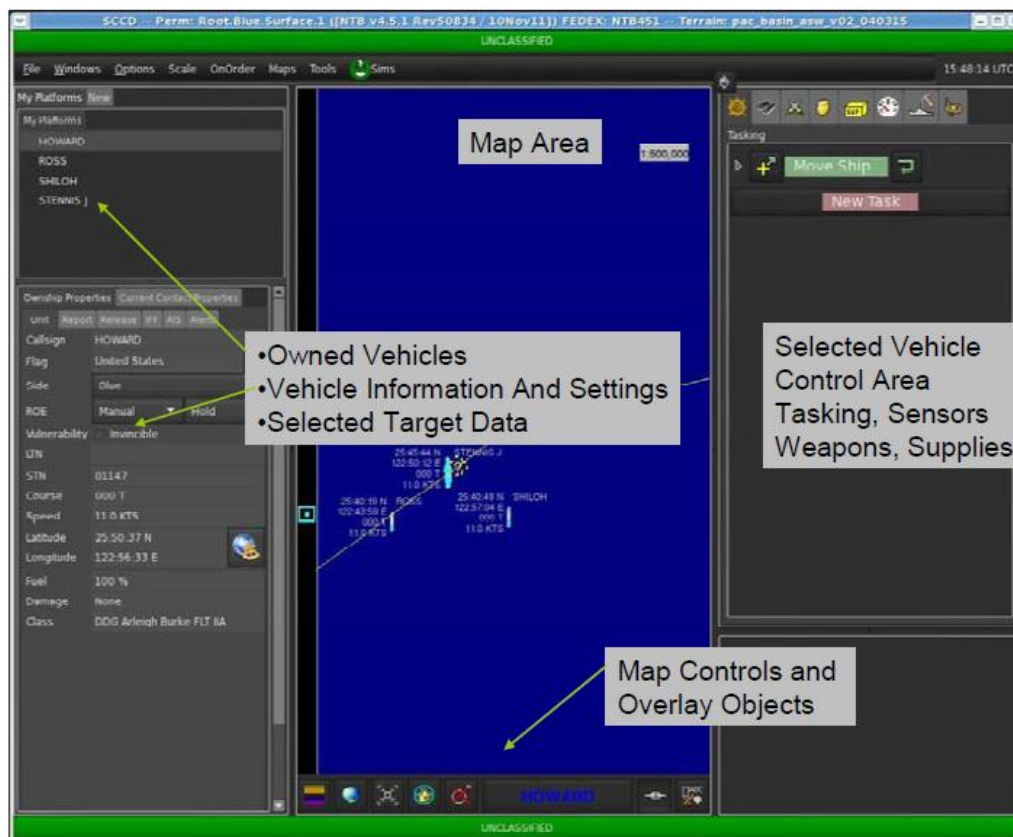


Figure 4. JSAF Sea Combat Commander Display (From Naval Warfare Development Command, 2011)

In the example shown in Figure 4, an Arleigh Burke Destroyer platform has been created and selected by the operator. The map panel displays platform icons, platform markings, maneuvering information, and sensor detections for the selected platform (Naval Warfare Development Command, 2011). There are tool icons just below the map area to allow map and overlay control. The left hand panel has a platform list at the top as well as parameters for the currently selected platform and contact information for sensed targets in the bottom section. The panel on the right provides maneuvering, weapons, and sensor controls for the selected platform.

B. ANTISUBMARINE WARFARE

1. P-3C Orion Multi-Mission Aircraft

The P-3C Orion is a land-based four-engine turboprop anti-submarine and maritime surveillance aircraft used by the U.S. Navy since 1969. The P-3C Orion was originally designed as a long-range anti-submarine warfare (ASW) patrol aircraft, but its mission has evolved to include surveillance of the battlespace over sea or land (United States Navy, 2009). The P-3C Orion, built by Lockheed Martin Aeronautical Systems Company, has four Allison T-56-A-14 turboprop engines, each with 4600 horsepower (United States Navy, 2009). The operational characteristics of the P-3C Orion are listed in Table 1.

Length	116.7 feet
Height	33.7 feet
Wingspan	99.6 feet
Unit Cost	\$36 million
Weight	Maximum Takeoff, 139,760 pounds
Airspeed	Maximum, 411 knots; Cruise, 328 knots
Ceiling	28,300 feet
Range	Mission Radius, 2,380 nautical miles; 3 hours on station at 1500 feet, 1346 nautical miles

Table 1. P-3C Orion Operating Characteristics (After United States Navy, 2009)

The current mission set of the P-3C Orion Multi-Mission Aircraft includes Anti-Submarine Warfare (ASW), Anti-Surface Warfare (SUW), Strike, and Intelligence, Surveillance, and Reconnaissance (ISR). Completion of these missions requires a highly trained crew, high tech sensors and equipment, and various weapons.

The P-3C Orion is manned by a crew of 11, consisting of five officers and six enlisted personnel. Three naval aviators (pilots) and two naval flight officers (NFO) make up the officer complement of the crew. One NFO is the Tactical Coordinator (TACCO), who is responsible for employing tactics and procedures and coordinating use of all sensors for each type of mission (Jorgenson, 1991). The other NFO is the Navigator/Communicator (NAV/COMM), who navigates the aircraft, monitors position and navigation systems, and conducts tactical communications (Jorgenson, 1991). The enlisted crew of the P-3C Orion is as follows: two flight engineers (FE), responsible to the pilots for monitoring engine and system flight station controls and indicators; two acoustic operators, responsible to detect, localize, classify, track, and report contact information gained by sonobuoys to the crew; one in-flight technician (IFT), who repairs damaged or broken equipment and assists the TACCO in deployment of ordinance; and

one electronic warfare operator (EWO), who utilizes various sensor systems and subsystems, as directed by the TACCO, and detects and analyzes targets of operational significance (Jorgenson, 1991). The layout of the P-3C Orion with crew seating positions is shown in Figure 5.

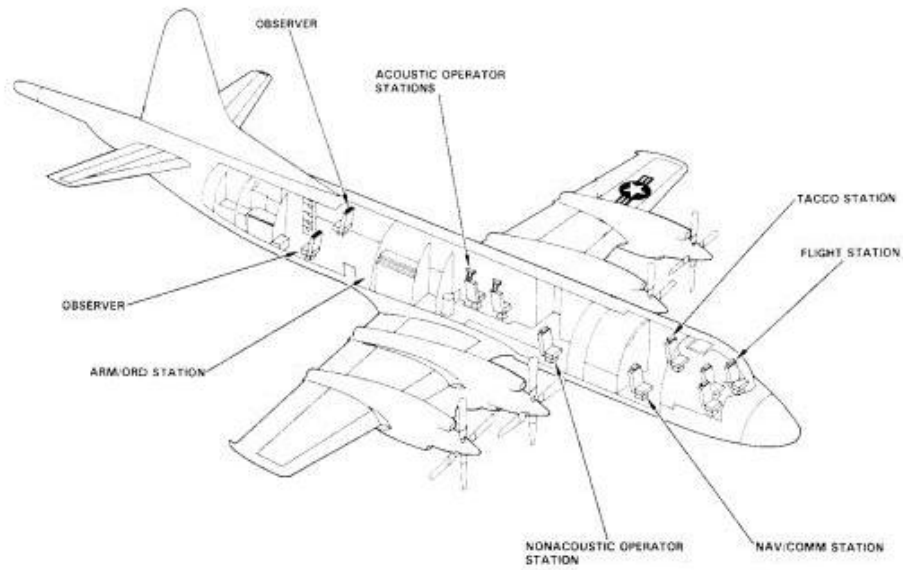


Figure 5. P-3 Orion Aircrew Seat Positions (From Jorgenson, 1991)

The P-3C Orion aircraft must employ a variety of sensors and equipment to complete the set of missions for which it is designed. An example of the sensors that would be used for ASW operations is depicted in Figure 6. The sensors of the P-3C Orion can be divided into acoustic and non-acoustic sensors (Jorgenson, 1991). The acoustic sensors are operated by the acoustic operator and the non-acoustic sensors are operated by the EWO (Jorgenson, 1991).

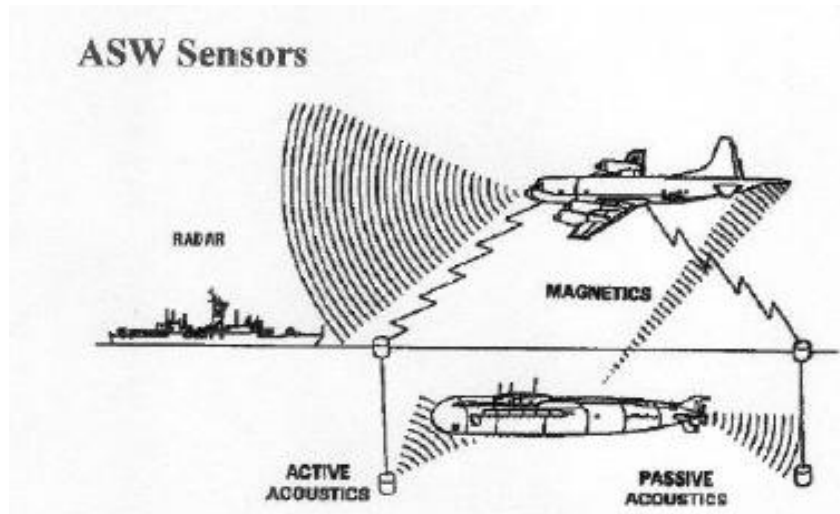


Figure 6. P-3 ASW Sensors (From Jorgenson, 1991)

The acoustic sensor of the P-3C Orion is the Single Advanced Signal Processor (SASP). To detect submerged contacts the P-3C Orion can deploy different types of sonobuoys to detect sound waves in the water. The SASP processes the acoustic data transmitted from the sonobuoys deployed by the aircraft (Jorgenson, 1991). The acoustic data is then displayed for the acoustic operators to analyze.

The non-acoustic sensors include the APS-115 or APS-137 radar, the ASQ-81 magnetic anomaly detection (MAD) system, the AAS-36 infrared detecting set (IRDS), and the ALR-66 electronic support measures (ESM) system. The radar is a vital sensor for the operation of the aircraft for both tactical and navigation purposes. It can be used to observe and detect surface vessels, submarines operating at periscope depth, aircraft, and other objects of military significance (Jorgenson, 1991). The radar is also a critical component for flight safety with weather and terrain avoidance. The APS-137 radar is found on the Anti-Surface Warfare Improvement Program (AIP) version of the P-3 and is more advanced than the APS-115 radar found on standard P-3 aircraft (Jorgenson, 1991). The MAD sensor senses anomalies in the Earth's magnetic field caused by a submarine using a helium magnetometer. It is used to correlate sonobuoy detections to confirm the location of a submarine. The IRDS converts infrared radiation emanating from a heat source, such as a diesel submarine recharging its batteries on the surface, to allow the P-3

operators to view targets if there is low visibility or at night (Jorgenson, 1991). The ESM system is used to identify electronic emissions from a submarine by passively scanning the radio frequency spectrum for intentional electronic transmissions. The system can be used to initially determine a bearing to a contact and eventually can triangulate the contact's position if it continues to radiate (Jorgenson, 1991). The acoustic and non-acoustic sensors available on the P-3C Orion aircraft allow the crew to operate as a team to detect and track a submarine whether it is submerged or operating on the surface.

The P-3C Orion is equipped with different types of offensive weapons to prosecute an enemy submarine once it is detected and identified. "The primary weapons used against submarines are torpedoes, mines, and bombs" (Jorgensen, 1991). Table 2 shows the various types of weapons typically carried by a P-3C Orion, although the number carried may vary depending on the mission to which the aircraft is assigned.

Weapon	Type	Number Carried	Note:
Mk-46	Torpedo	8	N/A
Mk-50	Torpedo	6	Upgrade from Mk-46
Mk-20 Rockeye	Cluster Bomb	10	247 bomblets
AGM-65 Maverick	Missile	4	IR weapon
AGM-84 Harpoon	SUW Weapon	6	All weather anti-ship missile
AGM-84E	Missile	4	Long-range, precision cruise missile
The Orion carries various types of bombs			
The Orion carries various types of mines			
The Orion carries various types of flares and rockets			

Table 2. P-3C Weapon Payload (From Jorgenson, 1991)

In addition to offensive weapons, the P-3C Orion has the ability to protect itself against an air-to-air missile threat. The AN/AAR-47 missile-warning set (MWS) will detect radiation associated with a rocket motor of an incoming missile and signal the aircrew of the incoming missile and the direction of the threat by sector or quadrant

(Jorgenson, 1991). The signal will also be sent to the AN/ALE-39 countermeasures dispensing system (CMDs). The CMDs will then disperse 60 passive radar decoy cartridges or infrared decoy cartridges (Jorgenson, 1991). The radar decoys or chaff are designed to confuse the radar of the incoming missile and the infrared decoys or flares are for diverting heat seeking missiles.

2. Sonobuoys

The U.S. Navy uses several different types of sonobuoys for tracking submarines, collecting oceanographic data and conducting underwater communication. All of the sonobuoys used by P-3's are standard A-size of length 36 inches and diameter 4 7/8 inches and can be launched from A-size tubes via pneumatics, free fall, or a Cartridge Actuated Device (CAD). They are powered by "either salt water activated magnesium or silver chloride, lithium chemistry, or thermal batteries" (United States Navy, 1998). The sonobuoys have a deployable acoustic signal source and reception of underwater signals of interest which are transmitted to any monitoring unit(s), such as MMAs, helos, or surface ships involved in ASW operations.

The conditions of the underwater environment can be monitored by Bathythermograph (BT) Sonobuoys and Low Frequency Analysis and Recording (LOFAR) Sonobuoys. The AN/SSQ-36 BT Sonobuoy is used to provide a thermal gradient measurement of the local water column to the monitoring unit (United States Navy, 1998). The AN/SSQ-57B LOFAR Sonobuoy is used to accurately measure ambient noise and can provide Sound Pressure Level (SPL) measurements (United States Navy, 1998). The use of these buoys gives the aircrew of the P-3 valuable information about the local ocean environment, which helps guide their selection of tactics.

The P-3C Orion can send a message to a friendly submarine using a Data Link Communications (DLC) Sonobuoy. The AN/SSQ-86 DLC Sonobuoy can be encoded by the aircrew prior to flight and provides limited, one-way acoustic communications to friendly submarines (United States Navy, 1998).

To track a submarine the P-3C Orion can use either passive or active tactics. Active tactics are not used as frequently due the possibility of alerting the submarine to

the fact that it is being tracked. There are a variety of active sonobuoys, but the most commonly used is the AN/SSQ-62E Directional Command Activated Sonobuoy System (DICASS) Sonobuoy. It provides “active sonar range, bearing, and Doppler information on a submerged contact” (United States Navy, 1998).

The primary method for tracking submerged contacts is the use of passive sonobuoys. The passive buoy most used is the AN/SSQ-53F Directional Frequency Analysis and Recording (DIFAR) Sonobuoy shown in Figure 7. The AN/SSQ-53F “combines a passive directional and calibrated wide band omni capability into a single multi-functional sonobuoy” (Sonobuoy Tech Systems, 2008). The AN/SSQ-53F Sonobuoy can operate in one of three acoustic sensor modes. A Constant Shallow Omni (CSO) sensor provides acoustic information at a fixed depth. The Calibrated Omni (CO) and DIFAR sensor modes allow operation at a selectable operational depth. “The buoy amplifies the underwater acoustics and provides directional data necessary to establish bearing to the source of the acoustic energy” (Sonobuoy Tech Systems, 2008).

The settings of the AN/SSQ-53F can be adjusted prior to loading and launching using Electronic Function Select (EFS) or after the buoy is deployed in the water with Command Function Select (CFS). The EFS selectable settings include Radio Frequency (RF) Channel, Buoy Life, Depth, Sensor, and Automatic Gain Control (AGC) level. Once the buoy is deployed, the RF Channel, Buoy Life, Sensor and AGC level settings can be changed via CFS (Sonobuoy Tech Systems, 2008). There are 96 RF channels to allow each buoy deployed to operate on a separate frequency, which is transmitted to the monitoring unit(s) with a 1 Watt transmitter to an UHF, single channel command receiver. The buoy operating life can be set to 0.5, 1.0, 2.0, 4.0 or 8.0 hours and there are four depth settings of 90, 200, 400, or 1000 feet (Sonobuoy Tech Systems, 2008).



Figure 7. AN/SSQ-53F DIFAR Passive Sonobuoy (From Sonobuoy Tech Systems, 2008)

3. Tactics

The aircrew of the P-3C Orion Multi-Mission Aircraft must apply proper tactics to use the sensors and equipment onboard to detect and track enemy submarines. The tactics can be broken down into categories of acoustic and non-acoustic tactics (Jorgenson, 1991).

The P-3C Orion uses the SASP to process signals from deployed sonobuoys to track diesel and nuclear submarines. The P-3 will typically deploy sonobuoys based on

some sort of cueing data such as detection from another sensor on the aircraft or a position report from another naval platform (Jorgenson, 1991). Once cueing data is obtained, the aircrew of the P-3 will lay down an organized deployment of sonobuoys in the vicinity of the datum position, which is called a sonobuoy pattern (Jorgenson, 1991). There are different patterns depending on the conditions of the ocean environment and the type of submarine being tracked with a specified geometry and spacing between buoys that will optimize the probability of detecting a submarine. The spacing and pattern of the sonobuoys is important because the P-3 has a limited number of sonobuoys and the detection range to the submarine could be only a few hundred yards (Jorgenson, 1991).

If a submarine is detected by one or more of the deployed sonobuoys the P-3 acoustic operators will analyze the broadband and narrowband noise signature of the submarine, with the help of the SASP, to attempt to determine the submarine's identity. "Once the submarine has been classified, it is the goal of the crew to maintain "contact" with the submarine" (Jorgenson, 1991). The crew will figure out the course and speed of the submarine and deploy sonobuoys along the track of the submarine to help maintain contact. The crew will have to be alert to any changes in course or speed the submarine makes to maintain contact.

There are several non-acoustic sensors available to the aircrew of the P-3C Orion to supplement the acoustic sensors to detect an enemy submarine, particularly if it is operating on the surface or at periscope depth. The APS-115 or APS-137 radar can detect surfaced submarines or exposed periscopes or snorkels. The submarine can use its ESM equipment to detect the radar from a P-3 and may submerge to avoid detection. The radar can detect a periscope at distances exceeding 10 miles, but the radar is not capable of classifying a submarine so another sensor is needed to corroborate the radar return (Jorgenson, 1991).

The IRDS, MAD, and ESM sensor systems are used to provide additional detection information about a submarine to help corroborate a radar return. The IRDS is used to detect the heat caused by a submarine operating near the surface, particularly if the submarine is a diesel recharging its batteries (Jorgenson, 1991). The MAD sensor is used to detect magnetic anomalies in the water and its effectiveness is determined by the

altitude of the aircraft and the depth of the submarine. A low altitude pass directly over a shallow submarine will provide the best opportunity of receiving a “MAD Hit” due to minimizing the slant range to the target. The MAD sensor may be susceptible to false detections from things like seamounts or shipwrecks when operating in shallow water environments (Jorgenson, 1991). The ALR-66 ESM system is capable of detecting electronic emissions from a submarine, such as radar or radio transmissions. The ESM can provide a bearing to the transmission source and can be used to analyze the parameters of the emissions to identify the type of radar being used (Jorgenson, 1991). The crew of the P-3C Orion has the training and expertise to use all of the sensors available to detect a submarine and confirm its identity and continue to track it as it transits through the water.

C. FINITE STATE AUTOMATA

Many agent based simulations, such as JSAF, use finite state automata as the formalism that structures the behaviors of entities in the simulation. Each entity in JSAF has different types of behaviors that act as a finite state automaton (or machine), which is “a device that can be in a finite number of states” (Daciuk, 1998). The device will switch between states if the proper conditions are met in the simulation. The switching of states is called a transition (Daciuk, 1998). The finite state machine can be represented in different ways such as directed graphs, state diagrams, or tables. Figure 8 shows a directed graph representation of a finite state automaton.

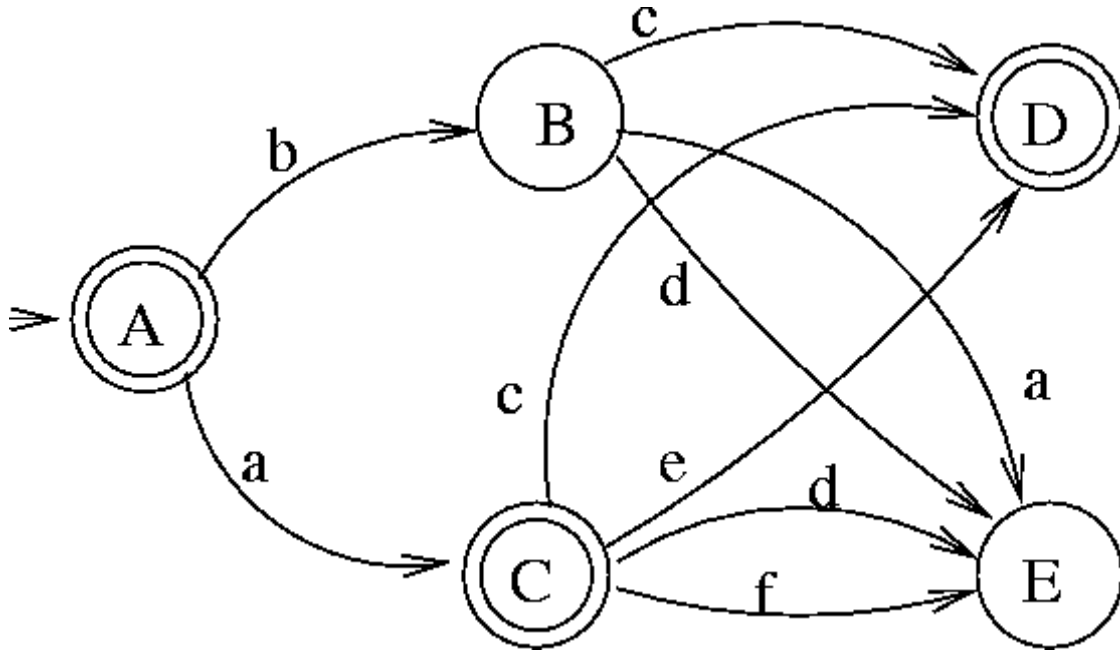


Figure 8. Sample Finite State Automaton (From Daciuk, 1998)

In Figure 8, each circle represents a possible state of the finite state automaton. The states with double circles are final states and state A is the initial state denoted by the arrow from the left with nothing at its origin (Daciuk, 1998). The arrows between states represent state transitions with labels denoting the input required to cause the state transition to occur. The set of inputs that may be accepted by the automaton is called the “language” (Daciuk, 1998) of that particular automaton. For an input to be accepted the automaton would have to be able to transition from the initial state to one of the final states. The automaton depicted in Figure 8 accepts the language $\{\epsilon, a, ac, ae, bc\}$ with ϵ denoting an empty input, which would be accepted since A is a final state. Inputs such as bd or af would be rejected since E is not a final state (Daciuk, 1998).

Finite state automata have many uses in today’s computing industry. They are used for language processing algorithms, control of transducers, image storage and recognition, engineering systems, and artificial intelligence applications. The entities in JSAF have different types of behaviors, which are controlled by finite state machines. For example, the behavior of a P-3C Orion to deploy sonobuoys is controlled by a finite state machine shown in Figure 9.

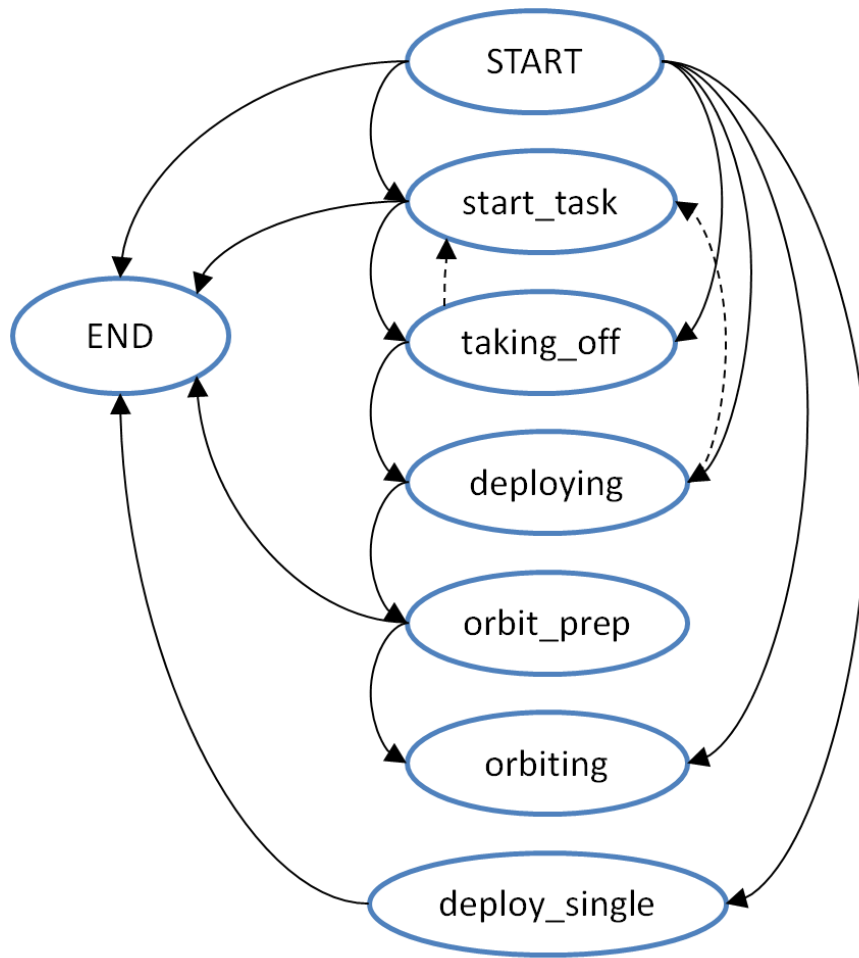


Figure 9. Finite State Machine for Deploy Sonobuoy Behavior in JSAF

D. MENTAL SIMULATION

When a person is tasked with performing an operation that is complex or not routine they will frequently use a technique called “mental simulation” to help them envision the sequence of actions required to accomplish the operation. Gary Klein, who has studied the way people make decisions for several years, describes mental simulation as “the ability to imagine people and objects consciously and to transform those people and objects through several transitions, finally picturing them in a different way than at the start” (1998). Before attempting to automate a task that may be performed by a JSAF

operator it is important to know how the operator might use mental simulation to determine the sequence of actions for the task.

When reviewing several cases where mental simulation was applied Gary Klein found some general similarities among mental simulations. They follow the same basic pattern: there is a starting point, a sequence of inputs, actions and outputs, and a final state or goal condition (Klein, 1998). Mental simulations are limited in complexity due to limits of human memory so they generally consist of three or less moving parts and six or less steps (or transition states) (Klein, 1998). There are techniques to get around the limitations on the number of moving parts and steps such as grouping several actions or parts together or using writing out of steps or diagrams to help with the mental simulation, but even diagrams can get complicated quickly and become difficult to follow (Klein, 1998). The more knowledgeable a person is in the subject of the simulation, the more complex the mental simulation can be.

A generic model of a mental simulation is shown in Figure 10. As shown, the person conducting the mental simulation first determines if they are trying to explain the past or project into the future. Once this is determined, the initial state, and final desired state are determined and causal factors are identified. The person performing the simulation then constructs a sequence of actions to transition from the initial state to the final state and evaluates the sequence “for coherence (Does it make sense?), applicability (Will I get what I need?), and completeness (Does it include too much or too little?)” (Klein, 1998). If there are any issues the person can reassess at the appropriate step.

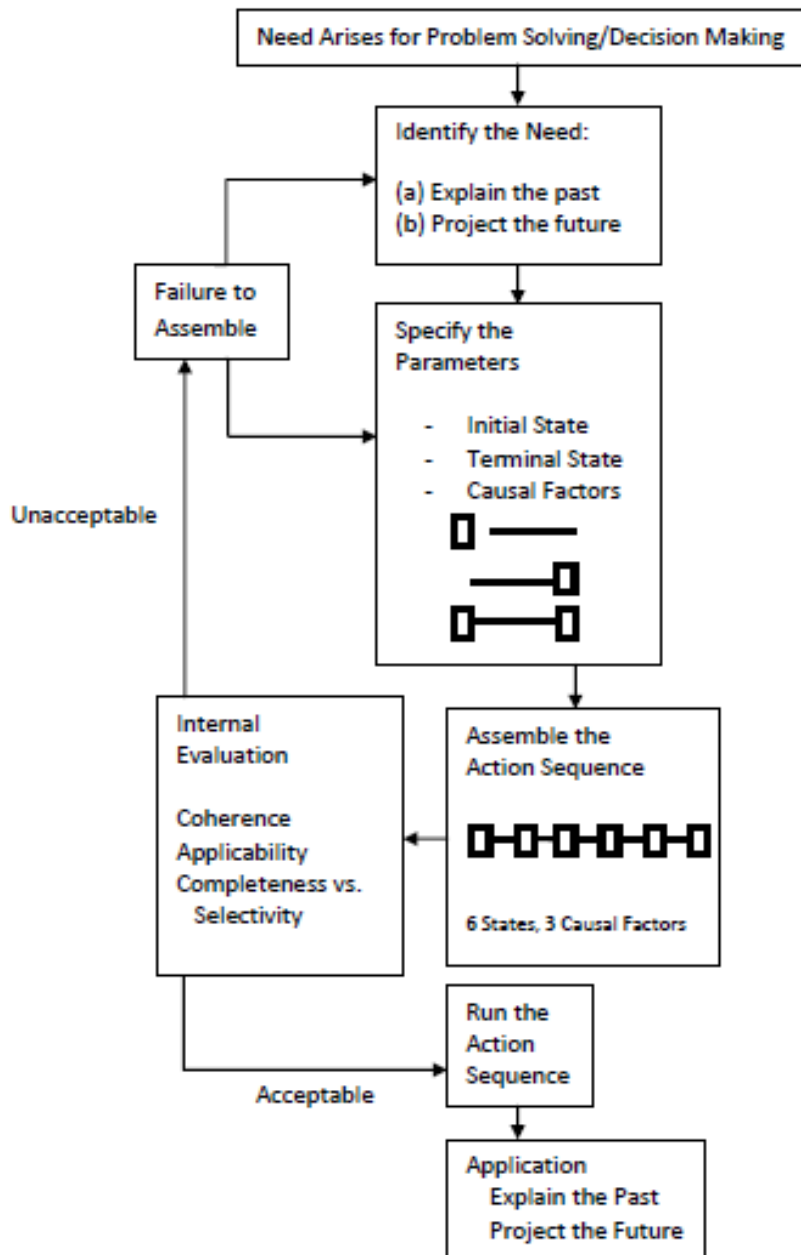


Figure 10. Generic Model of Mental Simulation (After Klein, 1998)

Mental simulation is a powerful tool for decision making in complex operations and is a likely mental model that would be used by a JSAF operator during a naval exercise. The mental simulation constructed by a JSAF operator for conducting a particular task or mission can be used as the template for constructing an algorithm for automating behaviors of the P-3C Orion aircraft.

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III. CURRENT EFFORTS IN SIMULATION AUTOMATION

There are several examples of efforts to produce realistic entity behaviors in military simulations to help reduce the need for pucksters and provide quality training. Virtual Puckster is designed to provide “behavior generation for Army small team training and mission rehearsal” (Colonna-Romano et al., 2009). Discovery Machine and EasyCog both attempt to provide improvements to JSAF behaviors. Discovery Machine provides an interface to allow subject matter experts (SMEs) to combine modular basic-level actions (BLAs) to develop a more complex behavior (Potts et al., 2010). The purpose of EasyCog is to provide a “software solution that automatically generates realistic behavior of friendly, hostile, neutral, or environmental entities in simulation” (Weyhrauch, 2010), particularly for Fleet Synthetic Training. These three technologies were chosen to study due to the similarity of the problem they are trying to solve to the problem of this thesis and because they each have a unique approach to solving the problem of entity behavior automation.

A. DISCOVERY MACHINE

The United States military has come to rely more on the use of simulation than in the past due to shrinking DoD budgets. Large scale training exercises can require simulation of several autonomous and semi-autonomous entities that must “behave in well-defined ways that correctly mimic their real-world counterparts” (Potts et al., 2010). Proper behaviors can help ensure training goals are met and prevent negative training due to unrealistic behavior from the simulated entities (Potts et al., 2010).

Discovery Machine Inc. has created a “behavior modeling framework for constructive entities which enables subject matter experts (SMEs) to develop complex entity behaviors using modular basic-level actions (BLAs) through an easy to use wizard-like interface” (Potts et al., 2010). They have developed behaviors for constructive

entities in JSAF for submarines, surface ships and rotary wing aircraft, and modeled behaviors of non-player characters in the Irregular Warfare Virtual Trainer for Joint Forces Command.

Discovery Machine provides GUIs known as behavior model authoring consoles for the SME to use while creating behaviors. The bulk of the work for creating behaviors for Discovery Machine is spent in the programming of BLAs. Once these are created a SME can create a mission or set of behaviors using BLAs “with no software engineering expertise in a matter of minutes” (Potts et al., 2010). The behaviors developed by SMEs can then be sent to a simulation, such as JSAF, without having to touch the simulation source code through an interface layer as shown in Figure 11.

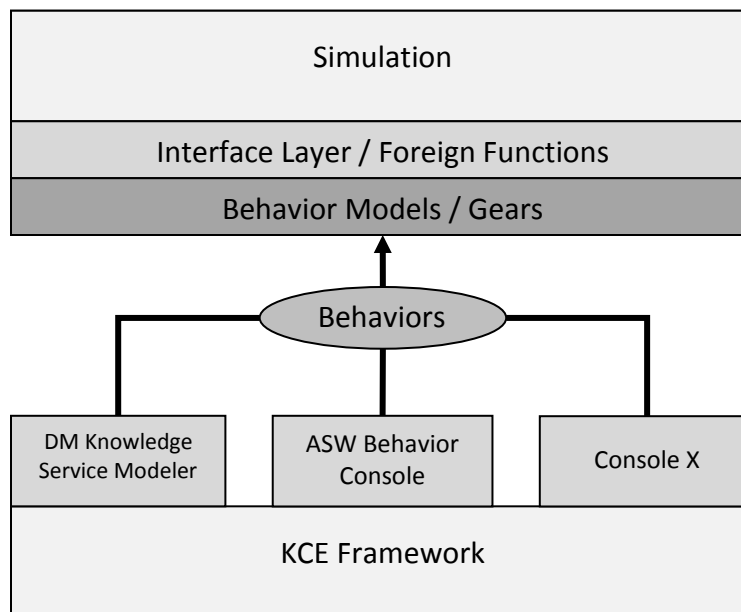


Figure 11. Discovery Machine High Level System Architecture (After Potts et al., 2010)

Once a behavior is built in Discovery Machine, operators can visually trace the execution of the behavior at runtime in a hierarchical view as shown in Figure 12. This allows operators and instructors to see the steps the behavior must go through and helps

understanding of why entities are performing particular actions (Discovery Machine, 2010). The advantages of this feature are that it “facilitates the improvement of behaviors and reduces frustration when entities behave in an unexpected manner” (Discovery Machine, 2010).

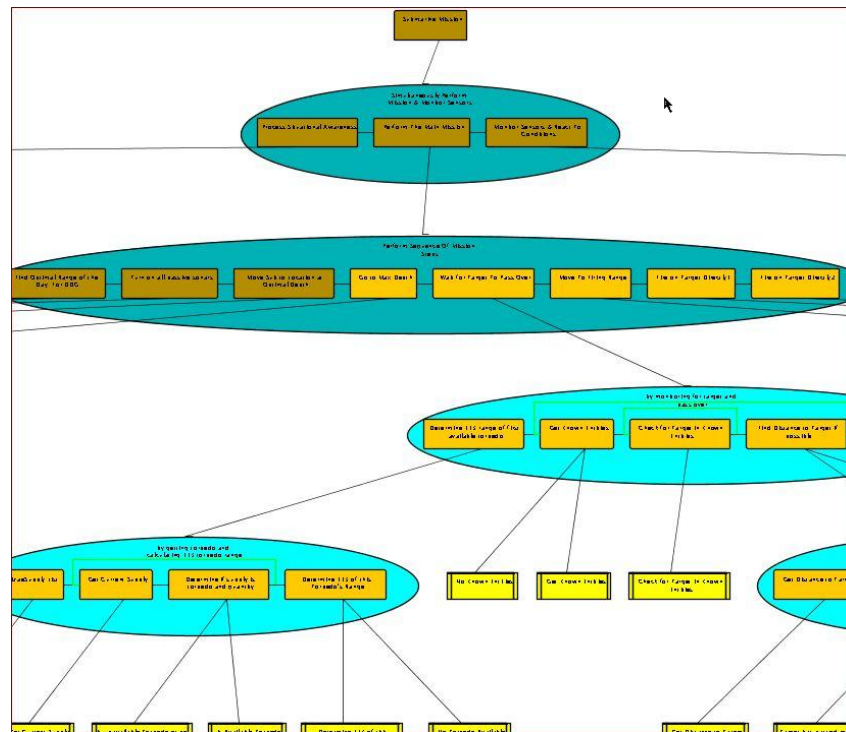


Figure 12. Visualization of Discovery Machine Behavior at Runtime

Discovery Machine has conducted validation testing of its surface ship behaviors in JSAF using a scenario with 60+ entities controlled by their behavior models (Discovery Machine, 2010). Without the Discovery Machine behaviors running, three operators were required to control JSAF entities and they were focused on the tasking 80 to 100% of the time during the test. When the same scenario was run with Discovery Machine behaviors running only one operator was required and was focused approximately 50% of the time to monitor the controlled entities. This shows an effective reduction in workload by the JSAF operators by at least a factor of five (Discovery

Machine, 2010). Discovery Machine Inc has shown that its behavior development software can help reduce operator workload by providing automated entity behaviors.

There are several advantages to the Discovery Machine Inc behavior modeling framework. It allows subject matter experts to develop behaviors with no software knowledge required, which helps ensure the behaviors provide realistic representation of real-world entities. It has a hierarchal behavior visualization tool, which provides a way to debug behaviors without programming. Finally, it has proven that it can reduce the workload of operators and allow simulation exercises to be run with fewer operators while still meeting training objectives. There are, however, some drawbacks to the Discover Machine software. Running Discovery Machine in the JSAF environment requires hardware to be connected to each machine at which JSAF entities are controlled. Each hardware setup costs between \$2000–3000 and there are over 70 stations for controlling JSAF entities during a major training exercise. Additionally, the Discover Machine software is not owned by NWDC so they do not have the ability to perform upgrades or maintenance on the behavior code as required for changes in tactics or other real-world changes.

B. VIRTUAL PUCKSTER

Recently, there has been a shift in the way the Army fights, from large force-on-force engagements to asymmetric operations, often in urban environments involving smaller groups such as platoons or squads (Colonna-Romano et al., 2009). This has led to a change in the “Army’s requirements for training and mission rehearsal exercises in deployed environments” (Colonna-Romano et al., 2009). Current synthetic exercise training tools for the Army require several pucksters and do not have the level of detail required to simulate coordinated actions of small teams.

Virtual Puckster is a project in development to help improve Army small team training and mission rehearsal. It is a Phase II Small Business Innovative Research project developed by Aptima and Total Immersion Software. Specifically, Virtual Puckster is an “application that will allow intuitive, real-time control of small groups of synthetic forces, that will offload the human puckster from the details of the coordination

of group behaviors, and that will allow the puckster to make rapid adjustments to team behavior as circumstances dictate” (Colonna-Romano et al., 2009). The Virtual Puckster system, shown in Figure 13, “consists of a graphical user interface (GUI), Group Behavior Engine (GBE) and a Group Behavior ‘Play’ library” (Colonna-Romano et al., 2009).

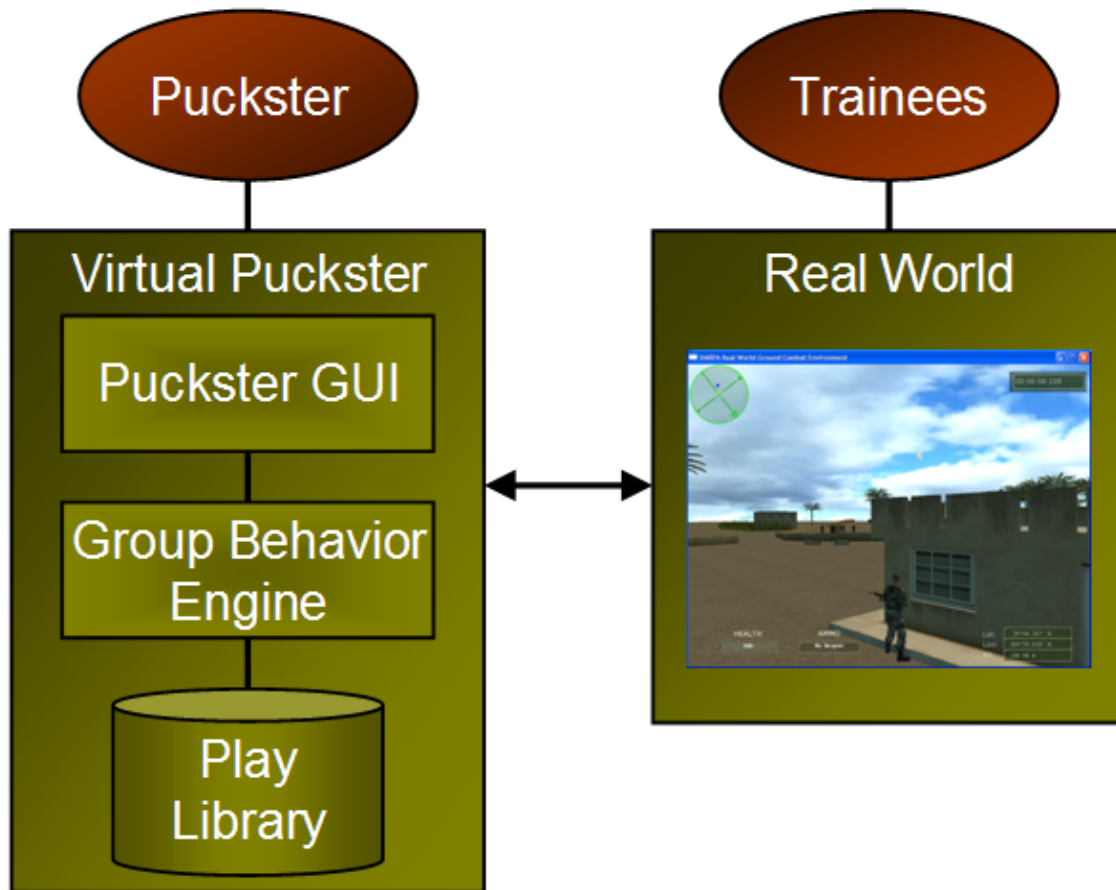


Figure 13. Virtual Puckster System (From Colonna-Romano et al., 2009)

The operator controls the Virtual Puckster system through the GUI by selecting the play that is appropriate for the training scenario. The puckster can provide inputs to the system to adjust the behavior from the GBE to tailor it to the conditions of the scenario. The adjustment to the play can be made real-time when “unexpected developments arise, such as surprising trainee behavior or equipment failure” (Colonna-

Romano et al., 2009). The benefit of Virtual Puckster is that it allows for control of a small team training simulation by one operator who is an expert in the training domain, but not necessarily the simulation. It also removes some of the burden from the puckster by providing behaviors for the small team while the puckster focuses on controls for only key members of the team.

C. EASYCOG

To help reduce the number of human operators, or “pucksters” required to run a JSAF simulation and improve the quality of training conducted using JSAF, Charles River Analytics Inc. is developing a software solution called EasyCog. The purpose of EasyCog is to “automatically generate realistic behavior of friendly, hostile, neutral, or environmental entities in simulation” (Weyhrauch, 2010). The behaviors modeled by EasyCog will be adaptable to various conditions and able to react to changes in the simulation environment or actions of trainees using the simulation, therefore, they will require minimum human intervention. EasyCog behaviors are designed to be reusable and adjustable to the training level required for a given exercise. The features, advantages, and benefits of the EasyCog software are summarized in Table 3.

Feature	Advantage	Benefit
Autonomous behavior	Human pucksters do not need to micromanage behavior	Cost savings by limiting need for human pucksters
Sound psychological and science-based realistic, human behavior	Behavior exhibits subtlety of human behavior under combat or stressful conditions	Training more realistic; enemies provide actual challenge
Modules and components	Model components can be built once and reused many times	Cost savings on model development and maintenance
Models of human performance and learning	System can support intelligent tutoring, after action review, and multiple levels of behavior complexity	Training can be tailored to expertise of trainee, maximizing the value of limited training time

Table 3. EasyCog Features, Advantages and Benefits (From Weyhrauch, 2010)

EasyCog has many features that could make it an ideal solution to reducing the number of operators required to simulate entities in JSAF, however, it is still in the early stages of development. In September 2012, EasyCog will be ready to demonstrate feasibility for Fleet Synthetic Training, which will be assessed by customers and subject matter experts. Then there will be another year before they are ready for a live program demonstration. The problem addressed by this research is limited to the automation of Multi-Mission Aircraft and will require a solution prior to the full development of EasyCog.

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IV. METHODOLOGY

After completing the literature review the next step is to attempt to answer the research questions for this study. There are three major steps of the methodology for answering the three research questions. The first step is to conduct an analysis of the operations conducted by JSAF operators to answer the first research question and to decide which behavior to automate. The next step is to investigate possible interfaces with the JSAF simulation system to answer the second question. The final step is to develop the automated P-3 task, which involves scoping and describing the task, solving the geometry of the problem and testing it with a prototype program, and finally implementing the task in JSAF. A test of the behavior is then conducted to evaluate the ability to reduce operator workload.

A. TASK ANALYSIS OF P-3 PUCKSTERS

Before producing automation software for P-3C Orion behaviors it is necessary to know how a P-3C Orion performs its mission as well as how a JSAF operator performs the task of simulating the aircraft. The first step of learning the process of both of these tasks is conducting a detailed literature review of the P-3C Orion Multi-Mission Aircraft and the JSAF simulation system, which is summarized in chapter 2 of this thesis. The next step is to conduct interviews with SMEs and observe the operation of simulation operators while they are simulating P-3 operations for an actual naval training exercise. Once this is completed, it can be determined which tasks require the most attention from the operators and can be automated in JSAF using the mental simulation approach.

Two trips were conducted to visit the Naval Warfare Development Command (NWDC) in Norfolk, VA for information gathering. The purpose of the first trip was to tour the facility, speak with JSAF and P-3 subject matter experts about the operation of JSAF for simulation exercises, and observe demonstrations of P-3s being simulated in JSAF. The second trip was to observe actual JSAF operators controlling P-3s for the TERMINAL FURY training exercise.

1. Facilities/Working Environment of JSAF Operators

The NWDC site in Norfolk, VA is a secure site where JSAF is maintained and operated for FST events. There are office areas for programmers, administrators and managerial staff, but the primary operation of JSAF is conducted in the main operational center. There are JSAF terminals arranged in concentric circles around a central control station where the referees of the simulation coordinate the event. For a given event the terminals are grouped according to the type of platform being controlled. For example, all of the friendly force MMA stations will be in close proximity to each other and the enemy submarine stations will be in a separate area.

Each JSAF terminal is equipped with two flat screen monitors, a mouse and a keyboard for the JSAF operator and a similar setup for the Liaison Officer (LNO) who acts as a buffer between the operator and the training audience of the exercise. There are also secure and non-secure phones for every few terminals for communicating with other JSAF terminals or with personnel involved in the exercise in other geographic areas. Each operator has a comfortable chair and ample desk space for notebooks and other papers as necessary.

Exercises will typically run for several days with a day or two of familiarization time for the operators. Once the exercise is commenced the operators and LNO's will work 12 hour shifts with 12 hours off until completion of the exercise. Operators will typically bring food with them for meals during their shift and eat at their station while continuing to control the P-3s under their cognizance.

The amount of attention required of the operators varies throughout the exercise. The operators are responsible for launching the P-3s, conducting any tasking they are assigned, and returning the P-3s to their operating base. The launch times are staggered so the operators have to be continually aware of the time until the next aircraft launch or return to base. Typical tasking consists of patrolling an area for high value unit protection, deploying sonobuoys to search for a submarine, and tracking and/or attacking a submarine. If any of these tasks occur while other P-3s need to take off or land it can be easy for the JSAF operator to become distracted and not complete a task on time. While

one individual task may not be particularly taxing on an operator, they need to be constantly vigilant of the status of all aircraft under their control.

2. JSAF Operators Training and Qualifications

JSAF Operator and LNO positions are manned from various sources for FST exercises. The JSAF operators consist of personnel from NWDC, some of whom are SME's on the platform they are simulating and some who are JSAF programmers with no platform specific experience, and other civilians who typically have previous military experience. The majority of the LNO's are manned from the reserves and are O-3s or O-4s from the community being simulated.

Prior to the commencement of the exercise the operators and LNO's are briefed on the scenario and training objectives of the exercise and given time to familiarize themselves with the JSAF interface and practice tasks with their platforms, such as creating and launching a P-3 or laying down a sonobuoy pattern. There is no training given on specific tactics for a certain platform, but tactical manuals are available to reference for a particular tactic. The operators may also be provided with "knee boards" to give them guidance on tactics. For example, a P-3 knee board would provide the basic steps and settings for deploying a sonobuoy pattern, such as buoy spacing, depth setting, and pattern selection.

There is a noticeable learning curve for the coordination between the exercise referees, the LNO's and the JSAF operators. The assignment of aircraft to operators is made by the LNO's and initially does not follow any sensible scheme such as assigning aircraft by similar mission types or the same geographic operating area. It was unclear who was responsible for creating overlays of P-3 operating areas in JSAF, which are assigned in the Air Tasking Order (ATO). It also took a shift or two for the operators to develop a good system for keeping track of the timing and tasking of their aircraft. There is always at least one operator per shift who is a SME on the platform to provide backup and guidance if a situation requires a special tactic.

Overall, there is not much formal training for JSAF operators. They primarily learn from on-the-job experience during exercises or from the shared experience and training that other operators and LNO's have from past exercises or military service.

3. Communications

There are several methods and paths of communication required to make a FST event a success. This research primarily focuses on the role of the JSAF operators who communicate with their LNO's and other JSAF operators in their vicinity. Therefore, only the communication methods of JSAF operators and LNO's will be described below.

The tasking for Multi-Mission Aircraft comes from two main sources. The ATO provides the timing and mission areas and types for all MMA flights. The ATO is in the form of a spreadsheet that lists the call sign, aircraft type, mission area, mission type, operating base and times of takeoff, on station, off station and return to base for each aircraft. Any deviation from the ATO will be communicated to the LNO via chat message from the task force commander. The LNOs are responsible for managing the assignment of missions to the JSAF operators. The operators receive a sheet of paper from their LNO for each mission for which they are responsible. The paper will have all pertinent times for the mission, a description of the tasking, load out information for sonobuoys and weapons and an area for recording comments during the mission. If new tasking is assigned, such as direction to track a possible submarine based on intelligence reports, the LNO will write down the tasking on a post-it note and pass it to the appropriate operator who will in turn update his tasking sheet and execute the new tasking.

The JSAF operators make several standard reports to the LNO's throughout the exercise. They report when P-3's are on station and off station and report information regarding detection and engagement of hostile submarines. When a submarine is detected the JSAF operator generates a "nine line" report, which has the contact type, track number, confidence level, sensor position, sensor type, contact position, contact

course/speed, date-time group and any amplifying remarks. The LNO receives the nine-line report and relays the information to the Combined Task Force (CTF) commander in charge of the exercise via MS chat.

Operators primarily rely on face to face communication with nearby operators and their LNO. They may also communicate with more distant JSAF terminals via phone or e-mail, or have the LNO contact the CTF headquarters over the secure phone or with Voice over Internet Protocol (VoIP). There are occasions when a surface ship JSAF operator will gain contact on a hostile submarine and the MMA operators will be informed of the submarine by the other operators, but will not receive tasking to track the submarine for up to 20 minutes due to the time to inform the CTF and for the order to be passed to the LNO from the CTF.

When a P-3 has completed its mission and returned to its home base the JSAF operator passes the sheet for the P-3 to a station where the data is entered into a database to keep a narrative of the entire exercise. Additionally the LNO informs the CTF via chat when the P-3 completes its mission. Another communication method available is Link 16, which is a military tactical data network. This network allows platforms to share a common tactical operational picture and can be used to exchange text messages or photographic images. The SCCD has a Link Management View window to create and send Link 16 messages, but this is seldom used by JSAF operators.

The predominant mode of communication for JSAF operators is face to face communications with information also being exchanged on paper and via chat as secondary means of communication. The verbal communications are not formal in nature and do not adhere to any known communication standard such as a ship's communication manual.

4. Operation of JSAF Terminals

The primary duty of the JSAF operator is to provide realistic behaviors for simulated entities in JSAF, which are reflected in the NCTE for FST exercises. The operator controls entities using JSAF in the SCCD mode or the PVD mode. Both modes are typically displayed and have similar functionality. The SCCD is a newer interface and

was designed to be more user friendly to ease the burden on the JSAF operators, however, some operators with previous experience using the PVD will rarely use the SCCD for controlling entities.

The main difference between the SCCD and the PVD is the level of situational awareness they provide to the JSAF operator. The SCCD only shows platforms controlled by that console or contacts sensed by their platform or fed into the common operational picture (COP) by other platforms in the exercise. The PVD shows ground truth data for all entities in the exercise regardless of which station is controlling them. This means the operator will have more information available when using the PVD, but the SCCD is more realistic because it only shows information that would actually be available to the crew of the platform. Since the SCCD is meant to be the primary means for controlling entities in JSAF this research will focus on SCCD operation.

The JSAF operator controls the SCCD using a mouse, keyboard and monitor for all input and output functions. The first step is to create an entity using the Platform Creation/Entity Selection section of the SCCD shown in Figure 14. The operator selects the “New” tab at the top and finds the desired entity using one of the filters available. Most operators use the marking filter and just start typing the name of the entity and the list is filtered similar to a word search program. Once the entity is displayed on the screen the user selects it by left clicking the mouse.

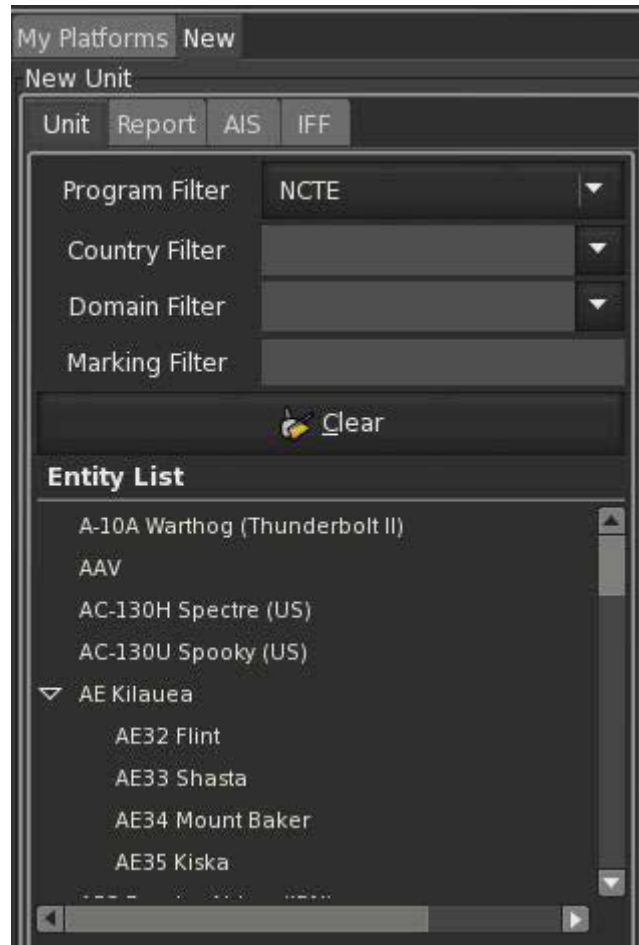


Figure 14. Platform Creation/Entity Selection Panel of the SCCD (From Naval Warfare Development Command, 2011)

The operator then proceeds to the Platform Creation, Specifics and Position Selection panel in the bottom left of the SCCD screen as shown in Figure 15. In this panel the operator fills in the “Call Sign,” “Mission ID” and “ATO ID” fields as necessary and specifies the position where the entity will be created by typing in the latitude and longitude or by selecting on the map area using the map tool (globe and sextant). Next the altitude or depth is specified and the orientation (course) of the entity is filled in and the operator left clicks the “Create” button to finish creation of the entity.

Call Sign	<input type="text"/>
Side	<input type="text"/>
Service	<input type="text"/>
Flag	<input type="text"/>
Mission ID	<input type="text"/>
ATO ID	<input type="text"/>
Latitude	<input type="text"/>
Longitude	<input type="text"/>
Altitude	<input type="text"/>
Depth	<input type="text"/>
Orientation	<input type="text"/>

Figure 15. Platform Creation, Specifics and Position Selection Panel of the SCCD
(From Naval Warfare Development Command, 2011)

Once an entity is created, the JSAF operator assigns a task to the entity related to the completion of its mission. In the case of P-3 operations for TERMINAL FURY, the operator first has the P-3 transit to its assigned operating area. If the assigned mission is to search the area for submarines the operator uses the SCC Maneuver Panel in the top right corner of the SCCD screen shown in Figure 16 to make the P-3 deploy a sonobuoy search pattern in its assigned area. When the “New Task” button is clicked a drop down menu appears with the tasks available for the platform selected. The operator selects the “Deploy Sonobuoys” task from the menu and the options for the deploy sonobuoys task comes up as shown in Figure 17.

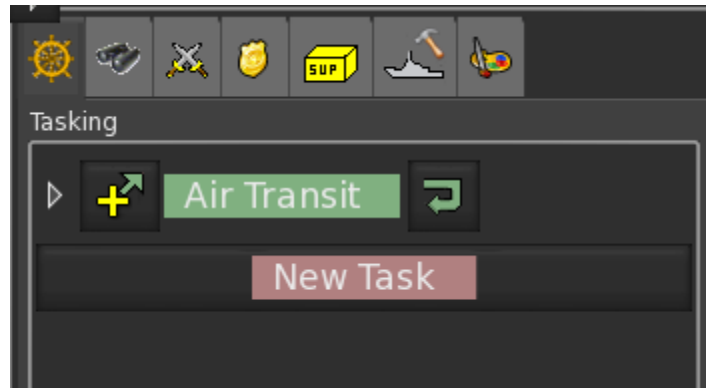


Figure 16. SCC Maneuver Panel

After the deploy sonobuoys task is displayed the operator specifies the parameters for the sonobuoy pattern to be deployed. Under “Deploy Type,” a drop down menu allows the operator to choose from use pattern, along route, or at point. Operators typically choose to plot a route using a line creation tool or they may choose a preprogrammed pattern from the “Pattern” drop down menu. Next the operator specifies the buoy depth setting, buoy duration, initial RF channel, whether to increment or decrement the RF channel, and the speed and altitude of the aircraft. Some of these settings just require the default setting to be used, therefore no manipulation is necessary. The JSAF operator then ensures the “Monitor Buoys” box is checked and the left clicks the “Apply” button to create the new task. This step does not cause the task to be executed immediately, so the operator can set up the sonobuoy pattern ahead of time while the P-3 is transiting to the operating area.

Further tasking for the P-3 is handled in a similar manner using the SCC Maneuver Panel. The most common tasks include transiting to or from an operating area, deploying sonobuoys (individually or in a pattern), patrolling an area, and conducting a torpedo attack on a hostile submarine. Another method for controlling the P-3 manually is with the steering wheel tool shown in Figure 18. With the steering wheel tool turned on the operator can change the P-3s speed, course, and altitude by clicking and dragging on the tool that appears above the platform graphic in the map panel of the SCCD. This tool is useful for maneuvering a P-3 into position for a torpedo attack.

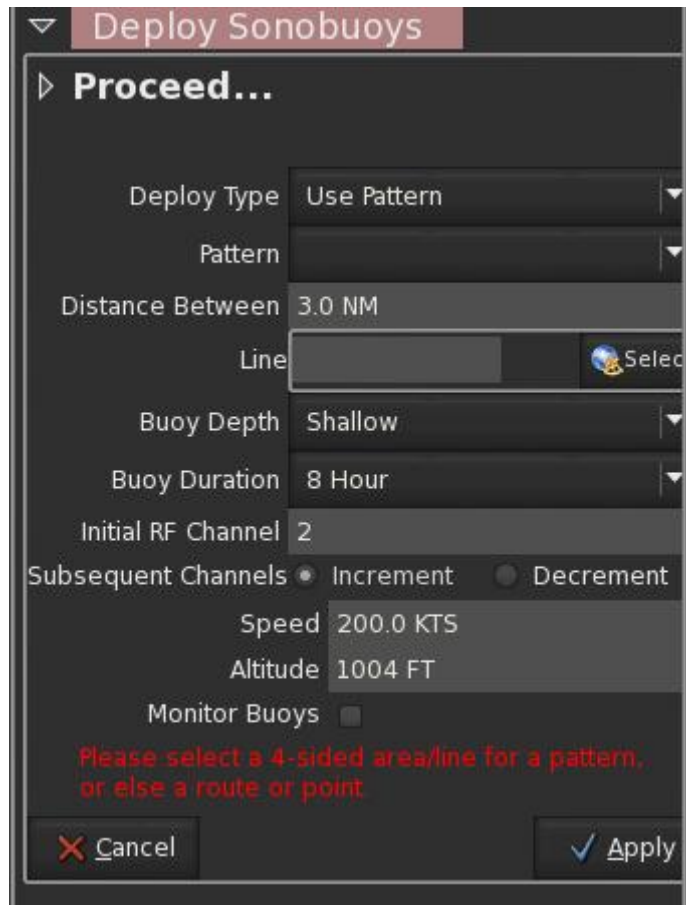


Figure 17. Deploy Sonobuoy Task (From Naval Warfare Development Command, 2011)



Figure 18. Steering Tool (From Naval Warfare Development Command, 2011)

If JSAF operators are not assigning tasks to a P-3 they still must monitor the aircraft under their control for detection of enemy platforms and be cognizant of the time until the next scheduled action. If a contact is detected by one or more of the P-3 sensors a datum icon will appear in the map panel in the location of the detection. The icons have different colors and shapes to indicate if the contact is hostile, friendly, neutral or unknown and to indicate the contact type, such as sub-surface, aircraft, or a surface ship. For detailed information about the contact, the operator can open the Track Status

window shown in Figure 19. The Track Status window shows all of the contacts available to the platform in a table format, which is helpful for generating nine-line reports. Additionally, the operator can see some of the contact information, such as course, speed and depth, in the map section when placing the mouse over the datum icon for a contact.

Delete	Status	Lost/Held	Time Late	GCCS LTN	GCCS Type	RU/STN/TQ	Callsign	Domain	Identity	Platform
<input type="checkbox"/>	🟡	Self	00:00:10		DDG	1142	ROSS	Surf	Friendly	DESTROYER
<input type="checkbox"/>	🔴	Self	00:00:03		CG	1147	SHILOH	Surf	Friendly	CRUISER
<input type="checkbox"/>	🔴	Self	00:00:11				SHQ	Installation	Friendly	HEADQUARTER COMPLEX
<input type="checkbox"/>	🟡	Self	00:00:00		DDG	1145	HOWARD	Surf	Friendly	DESTROYER
<input type="checkbox"/>	🟡	Held	00:00:10		CVN			Surf	Friendly	AIRCRAFT CARRIER (CV)
<input type="checkbox"/>	🟡	Held	00:00:10		CVN		STENNIS J	Surf	Friendly	AIRCRAFT CARRIER (CV)

Figure 19. Track Status Window of the SCCD (From Naval Warfare Development Command, 2011)

The SCCD has many other functions that are not used as frequently by the JSAF operators. Other activities the operators are responsible for include plotting of overlays to indicate operating areas for their P-3s and saving the scenario periodically in case there is a system crash. None of the actions performed by the operators take very long, but the operators can become overwhelmed or distracted when controlling several P-3s simultaneously and tasks start to pile up when the situation is dynamically changing. In some cases the operators will refer to the PVD to get a better contact picture so they can allocate their attention to areas with more activity, such as an area with a hostile submarine nearby.

5. Areas for Improvement

After speaking to SMEs and observing JSAF operators conducting a fleet exercise, several areas were noted that could use improvement and lead to a reduction in the number of operators required for an exercise. There are issues with the organization

of the exercises and training of the JSAF operators as well as entity behaviors that could be automated to make the JSAF operator's job more efficient.

Several of the JSAF operators observed were either unfamiliar with the operation of the SCCD or proper tactics for the platform they were controlling. A short training session on the operation of the SCCD and P-3 tactics implementation in JSAF before the start of the exercise would be helpful. There is extensive documentation on operation of the SCCD and P-3 tactics, but it would make it easier on the operators if there were condensed guides or tutorials for them to refer to while they are busy controlling multiple P-3s.

Three organizational issues were noted during the TERMINAL FURY exercise. The JSAF operators were distracted on several occasions by having to produce overlays for new operating areas assigned by tasking messages. Many of the overlays were created in JSAF prior to the start of the exercise, but there was not a designated person for entering new areas as they were received. Another inefficient practice was the assignment of P-3 to the operators. Early in the exercise the LNOs were just randomly assigning aircraft to the operators as they were received on the ATO. A scheme for assigning P-3s was eventually developed, but it took more than an entire shift to get the P-3s organized. Each operator should only be assigned P-3s in a certain geographic area or mission type, which will help the operator to focus on a limited scope of operations and help the team organization. The last area of organization that needs improvement is the tracking of mission timing by JSAF operators. The operators used their mission assignment papers to keep track of the times for the next mission event (take off, return to base etc.), with the papers in a pile in no apparent order. A timeline program with a row for each mission and the event times annotated would alleviate the possibility of operators being late to complete events.

Two P-3 tasks were identified that require a large amount of attention from the operator. The first task is conducting a torpedo attack on an enemy submarine. This task requires the operator to select a torpedo from the weapon inventory or the P-3, select the proper torpedo settings for the attack, manually guide the P-3 to the proper course, speed and altitude for dropping a torpedo and then drop the torpedo with the correct timing to

have a successful attack. This process takes a significant amount of time and attention for the operator to complete and it requires knowledge of the proper tactics and settings to be completed in a timely and accurate manner. A torpedo attack behavior would allow the operator to pay attention to tasking for other P-3s and would ensure a properly executed attack in accordance with P-3 tactical manuals. The second task that should be automated is the placement of sonobuoys to track a submarine once it has been detected and is exiting the sonobuoy pattern that has already been placed by the P-3. This task requires the operator to pay close attention to the course and speed of the submarine so the sonobuoy pattern can be adjusted for changes in the submarine's track. It also requires accurate placement of the sonobuoys in complex geometrical patterns using proper tactics. An algorithm for placing the sonobuoys would be more accurate and realistic and the behavior could keep track of the submarine's track and adapt as required without dropping unnecessary sonobuoys. The behavior could be programmed to provide an alert to the operator if contact is lost with the submarine to allow the operator to take control of the P-3 and regain contact with the submarine.

Of the areas mentioned above for improving the workload of P-3 JSAF operators, the plotting of overlays, torpedo attack on a submarine and sonobuoy placement are the three that could be addressed with automation software. The remainder of this research will focus on the automation of sonobuoy placement for tracking a submarine for several reasons. The sonobuoy placement behavior will have the greatest impact on relieving the workload of the operators. There already exists a task in JSAF for deploying sonobuoys in a set pattern that could be extended to adaptively placing sonobuoys with relative ease. Last, this work will show the ability to automate a complex task using the mental simulation framework and provide an example of the process for automating behaviors in JSAF that can be repeated for future behaviors.

B. DETERMINING THE BEST JSAF INTERFACE

After observing JSAF operators controlling P-3s for an exercise and speaking with SME's the next step was to determine the best way to interface with JSAF to create an automated adaptive sonobuoy behavior. Based on literature review and conversations

with JSAF programmers, three options were identified for implementation of the algorithm: 1) Create the behavior with Discovery Machine software and connect to JSAF using their software; 2) Use a standalone program to run the algorithm and communicate with JSAF via an interface, such as a user-bot; or 3) Program the algorithm directly into the JSAF source code. Each option will be discussed below and pros and cons will be given for each approach.

1. Discovery Machine

The Discovery Machine software allows SME's to author behaviors for JSAF entities by piecing together basic-level actions (BLA) they have programmed. Once a behavior is created, Discovery Machine has a visualization tool that allows tracing the steps executed as the behavior runs. If the behavior passes the checks using the visualization tool it can be run in JSAF for testing using the Discovery Machine interface layer. Discovery Machine Inc. has an office in Norfolk, VA and works closely with JSAF developers, which could be useful if any problems were encountered during the creation of the adaptive sonobuoy placement behavior.

There are several advantages to using the Discovery Machine approach for automating P-3 behaviors. Potts et al. (2010) list the following advantages of the Discovery Machine Behavior modeling approach:

- Rapid development of new behaviors for customized training scenarios
- Expert domain knowledge captured within the modeling tools to assist building more intelligent behaviors
- Transparency of behaviors for subject matter experts during and after development
- Transparency of behaviors at runtime, easing the debugging process and exposing decision making process of entities to operators

Other advantages include the fact that knowledge of the JSAF source code would not be required and that there would be minimal coding involved with this approach.

There are also several drawbacks to using the Discovery Machine software to create behaviors for the P-3 aircraft in JSAF. The primary concern of the JSAF programmers was the fact that they would not have proprietary rights to the code for the behavior developed from this research if Discovery Machine was used. Therefore, they would have to rely on Discovery Machine to maintain the code and ensure the behavior was up to date with the latest tactical publications. NWDC would also have to pay approximately \$2,000 annually for each terminal that has the Discovery Machine software connected. Additionally, the BLA's for fixed-wing aircraft are not fully developed (Discovery Machine, 2011) so the project timeline does not allow for waiting for full development of the BLA's.

Based on the advantages and disadvantages of the Discovery Machine approach, it was decided not to use this method for developing the adaptive sonobuoy placement behavior. However, if NWDC were to commit to funding the connection of Discovery Machine to multiple JSAF terminals and Discovery Machine completed the programming of fixed-wing aircraft BLA's, it could be a viable solution for future behavior development efforts.

2. External Program

A second option for implementing an adaptive buoy placement behavior in JSAF is to program the algorithm as stand-alone software and have it communicate with JSAF through an interface. The interface would most likely involve communicating with JSAF using High Level Architecture (HLA) protocols to get data from the simulation and provide inputs for controlling the behavior of the P-3. Another option is the use of a userbot to essentially take control of the display, mouse and keyboard of the JSAF terminal and perform the actions that would be taken by a JSAF operator from a remote program.

This approach shares some advantages and disadvantages with the Discovery Machine method as well as some additional considerations. Similar to Discovery Machine, this method would not require learning the JSAF source for behaviors, but the interface method would require some coding, which could be extensive. Also in common

with Discovery Machine is the fact that the program would be separate from JSAF so it would have to be incorporated into the JSAF update process. However, the program would be owned by NWDC at the end of the project so they could make changes as desired. Additional advantages to using a separate program are that any software language can be used for the algorithm and the debugging process would be faster than if the algorithm was coded directly into the JSAF source code. The disadvantage is that a large amount of time would be spent learning the interface protocols for connecting to JSAF instead of focusing on behavior automation, which is the primary purpose of the research.

Using an external program for the adaptive sonobuoy placement behavior was eliminated as an option after weighing the benefits and drawbacks of the approach. The software engineers at NWDC expressed their desire for the behavior to be part of the JSAF code and it is undesirable to spend too much time and effort learning the JSAF interface protocols. However, an external program is used in the development of a prototype to test the geometry of the sonobuoy patterns before implementation in JSAF.

3. Direct Coding in JSAF

The last option considered for implementing the adaptive sonobuoy placement behavior was programming the behavior directly in the JSAF source code. This could be achieved by creating a new task that monitors for enemy submarines and triggers an adaptive sonobuoy placement task, or by modifying the existing task for deploying sonobuoys.

There are several advantages to this approach. The primary consideration is that the code for the algorithm would be a part of JSAF and would be owned by NWDC for updates and maintenance, and the task can be upgraded to mimic classified and evolving tactics by NWDC. Another advantage is the support available for coding in JSAF. There are two workstations with an unclassified version of JSAF installed at the Modeling, Virtual Environments, and Simulation (MOVES) Institute at the Naval Postgraduate School (NPS) available for use by students and faculty. There are also personnel at NWDC working with NPS to help with any coding questions and to evaluate the

effectiveness of the algorithm. The last advantage is that time that would be spent learning the interface protocols of JSAF can be dedicated to developing and implementing the behavior in JSAF.

As with any technique, there are some drawbacks to programming the adaptive sonobuoy behavior directly in the JSAF source code. The code for JSAF is highly complicated with approximately 1200 libraries and 5 million lines of code. In addition to having to learn a complex program, there is no flexibility in the choice of program language for the algorithm. The last disadvantage is the debug cycle time. After making an alteration to the code, it takes close to two minutes to rebuild JSAF and run a scenario to test the change.

The disadvantages of direct programming in the JSAF code mean that it may take longer to implement the algorithm; however, the fact that the code will be owned by NWDC and can be upgraded to a classified version of the behavior outweighs the time disadvantage. Therefore, the decision was made to implement the adaptive sonobuoy placement behavior by programming it directly in the JSAF source code.

C. P-3 TASK AUTOMATION DEVELOPMENT

1. Scope of the Task

For the initial development of the adaptive sonobuoy placement task the behavior is limited in scope to solving the basic geometry and behavior of the algorithm. The first implementation of the behavior will assume that there will only be one submarine in the geographical area to which the P-3 is assigned. The algorithm will only account for the use of passive sonobuoys, even though there are rare occasions where active sonobuoys may be used. There are some cases where the crew of the P-3 may decide to vary the buoy life setting on the deployed sonobuoys, but this will not be accounted for in the first implementation and buoy life will be set at eight hours. The assumed environment will be open-ocean, so accounting for littoral regions will be considered after the baseline behavior is solved. If the P-3 has to track a submarine for an extended time period the aircraft would eventually run out of sonobuoys and another asset would have to assume

the tracking duties or the P-3 may transition to another air asset's operating area and turn over tracking duties. This scenario will not be modeled in the first behavior implementation.

There are also limitations to the adaptive sonobuoy placement behavior due to the fact that the submarine tracking tactics of the P-3 are classified and this research is unclassified. Any numerical settings for the initial algorithm will be approximations of actual classified values and the tracking task will be functional, but will not display actual tactical operations.

2. Description of Task

Prior to implementation of the adaptive sonobuoy placement behavior in JSAF, a detailed description of what the behavior should look like and the steps to perform the behavior is required. An initial description of the task including display considerations, the geometry of the buoy pattern, and the steps of the behavior was developed using the mental simulation framework and improvements were made based on suggestions of SME's at NWDC. The concept for the initial behavior implementation is as follows:

a. Graphical User Interface

- Add a "Track Hostile Sub" checkbox to the Deploy Sonobuoys task that already exists in JSAF as shown in Figure 20.
- Alert icon in "My Platforms" and accompanying message in "Alerts" tab to tell the operator that a contact has been classified as a hostile sub.
- Alert icon and accompanying message to tell the operator if contact is lost with the submarine.
- Remove the route overlay for the current sonobuoy pattern and add the overlay for the new route.

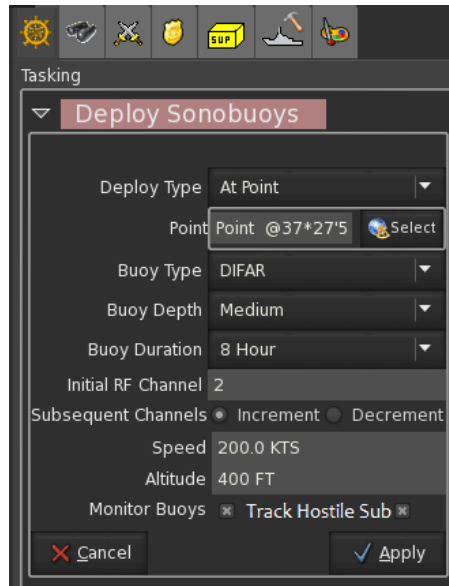


Figure 20. Track Hostile Submarine Checkbox

b. Deploying Sonobuoys

- Get course, speed, depth, and position of submarine (based on sensor data).
- Get position of sonobuoys already being monitored by the P-3.
- Periodically, calculate position and time to deploy next sonobuoy based on projected submarine course and speed and existing sonobuoy field.
- If a sonobuoy is needed:
 - Determine shortest route to deploy sonobuoy.
 - Set sonobuoy parameters.
 - Position the P-3 to drop sonobuoy (heading, speed, altitude).
 - Drop sonobuoy when at release location.
- If no sonobuoys are needed:
 - Orbit last sonobuoy position until next buoy is needed.

When calculating the position to drop the next sonobuoy the program will determine the two closest sonobuoys to the submarine and then drop a new sonobuoy such that it makes an equilateral triangle, on the side the submarine is traveling towards,

with the two existing sonobuoys. The algorithm will check positions along the submarine's track and check if a sonobuoy is needed for each position. A sonobuoy is needed at a certain position when the submarine is not within the detection range of less than three sonobuoys. The submarine can be tracked with less than three sonobuoys in contact, but the accuracy of the cross-fix obtained by three sonobuoys is better. Therefore, the goal of the algorithm is to have three sonobuoys tracking the submarine at all times.

An overhead-view example of the geometry that may be encountered when implementing the behavior is shown in Figure 21. In this illustration, the red buoys were deployed by a P-3 based on an intelligence report and the submarine is detected heading to the northeast. Based on the submarine's course, the next buoy deployed is the green buoy, which makes an equilateral triangle with buoys 3 and 4. Then the submarine maneuvers to the northwest and the algorithm places buoy 6 to make an equilateral triangle with buoys 4 and 5.

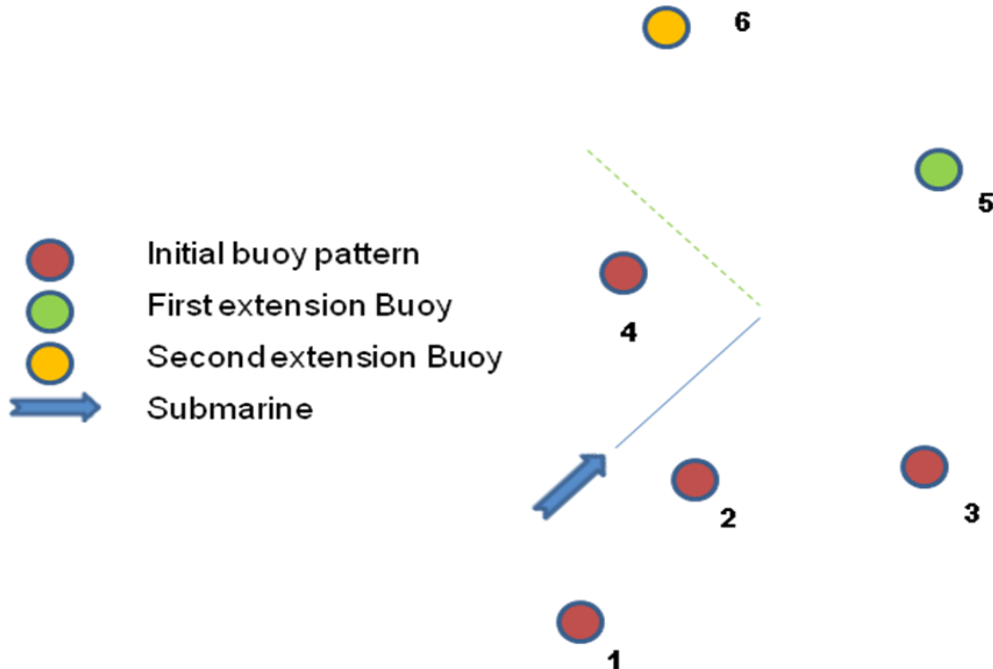


Figure 21. Geometry for a Typical Sonobuoy Pattern Extension

The time at which the P-3 drops a sonobuoy to extend the pattern is also important to ensure sonobuoy inventory is preserved while still maintaining contact on the submarine. If a sonobuoy is dropped too early and the submarine maneuvers, the sonobuoy would then serve no purpose. Conversely, if the sonobuoy is dropped too late there is a risk that the submarine may be out of range of the sonobuoy field and contact may be lost. Therefore, the algorithm must take into account the time it will take the submarine to reach the point at which it will only be in range of two sonobuoys, the time for the P-3 to transit to the drop point, the time for the sonobuoy to reach the water and the time for the sonobuoy to sink to its ordered depth and be ready to detect a submarine.

3. Geometry of Sonobuoy Pattern

Once the algorithm determines the two sonobuoys that are closest to the submarine's position the next step is to determine the correct location to drop the sonobuoy. The position of the existing sonobuoys and the velocity vector of the submarine can be obtained from the simulation and can be used with vector math and geometry to calculate the new sonobuoy position. The geometry for calculating the new sonobuoy position is shown in Figure 22. The JSAF environment is three dimensional, therefore each symbol in Figure 22 is a three dimensional vector.

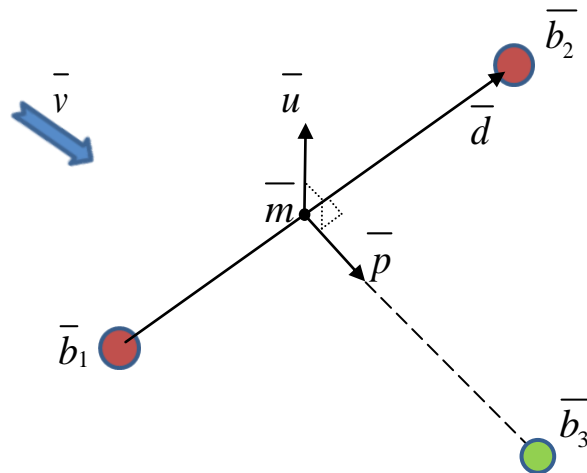


Figure 22. Sonobuoy Placement Geometry

The first step towards finding the new sonobuoy placement position \bar{b}_3 is to calculate the difference vector between the two closest sonobuoy positions \bar{b}_1 and \bar{b}_2 as follows:

$$\bar{d} = \bar{b}_2 - \bar{b}_1$$

Next, the midpoint between the two closest sonobuoy positions must be calculated as follows:

$$\bar{m} = \frac{\bar{b}_1 + \bar{b}_2}{2}$$

The vector pointing in the up direction \bar{u} can be obtained from the simulation, which will be described in the section for implementing the behavior in JSAF. The next step is to find the vector \bar{p} that is perpendicular to both the up vector \bar{u} and the difference vector \bar{d} . The vector \bar{p} must be perpendicular to the up vector to ensure the new sonobuoy is in the same plane as the two closest sonobuoys. This does not account for the curvature of the earth, but due to the close proximity of the sonobuoys the effect is insignificant. The vector \bar{p} is perpendicular to the difference vector to ensure it points to the new sonobuoy position. Therefore, the vector \bar{p} has to satisfy the following equations:

$$\bar{p} \cdot \bar{u} = 0$$

$$\bar{p} \cdot \bar{d} = 0$$

Since the vectors are three dimensional, there are two equations with three unknowns in the equations above. Only the direction of the vector \bar{p} is of significance, so one of the components of \bar{p} , such as p_z , can be set to one leaving two equations with two unknowns, which can be solved with simple algebra. Solving the equations gives the components of \bar{p} as follows:

$$p_x = -\frac{u_z}{u_x} - \left(\frac{u_y u_z d_x - d_z u_y u_x}{d_y u_x^2 - d_x u_x u_y} \right)$$

$$p_y = \frac{u_z d_x - d_z u_x}{u_x d_y - u_y d_x}$$

$$p_z = 1$$

The perpendicular vector \bar{p} is converted to a unit vector of length one by dividing each component by the length of the vector as follows:

$$\hat{p} = \frac{\bar{p}}{\|\bar{p}\|}$$

The position of the new sonobuoy could fall on either side of the two closest sonobuoys depending on the course of the submarine. The new sonobuoy must be placed on the side the submarine is traveling toward, which can be determined mathematically by taking the dot product of the submarine's velocity vector \bar{v} and the perpendicular vector \bar{p} . If the dot product $\bar{v} \cdot \bar{p}$ is positive or zero then the position of the new sonobuoy can be found as follows:

$$\bar{b}_3 = \bar{m} + \frac{\sqrt{3}}{2} \|\bar{d}\| * \bar{p}$$

Otherwise, the new sonobuoy will be placed on the opposite side of the two closest sonobuoys with its position calculated as follows:

$$\bar{b}_3 = \bar{m} - \frac{\sqrt{3}}{2} \|\bar{d}\| * \bar{p}$$

The adaptive sonobuoy placement algorithm will use this method for determining where to drop the next sonobuoy once it has determined that one is needed at some point along the submarine's track. This technique is not an actual Anti-Submarine Warfare tactic, but it does an adequate job of maintaining at least three sonobuoys in contact with a submarine regardless of its course or speed.

4. Prototype Program

Before implementing the adaptive sonobuoy placement behavior in JSAF, portions of the algorithm were tested using a prototype program completely separate from JSAF. Since JSAF already has tasks for routing P-3's to drop sonobuoys this portion was not implemented in the prototype program. The purpose of the prototype was to test the geometry of the sonobuoy pattern with a maneuvering submarine to ensure there was adequate sonobuoy coverage for a variety of submarine maneuvering patterns.

There is a wide variety of software available that would be suitable for testing the algorithm. It was desired to have a visual representation of the submarine and sonobuoy field and the ability to control the submarine using mouse and/or keyboard commands. The software chosen for creating the prototype program was the DarkGDK game development kit software. DarkGDK uses C++ as its program language and is free of charge with Microsoft Visual C++ 2008 Express Edition. This software was chosen for several reasons. First, the software is free and is in the same programming language as the JSAF source code, which will ease the transfer of the algorithm to JSAF. Additionally, the software meets all of the needs of the prototype program and is easy to use. The research team also has previous experience using the DarkGDK toolkit, which minimized the time spent learning the software.

Since the SCCD panel in JSAF shows an overhead, two-dimensional view of the entities, the prototype program was implemented as an overhead, two-dimensional representation. Icons for representing the submarine, existing sonobuoys and newly placed sonobuoys were created using Microsoft Paint and coordinates were specified for placement of the submarine and existing sonobuoys in a pattern similar to the example in Figure 21. The initial setup of the submarine and sonobuoys for the prototype program is shown in Figure 23. The blue circles represent the sonobuoys dropped by a P-3 prior to gaining the submarine and the thin black circles show the maximum detection range of the sonobuoys.

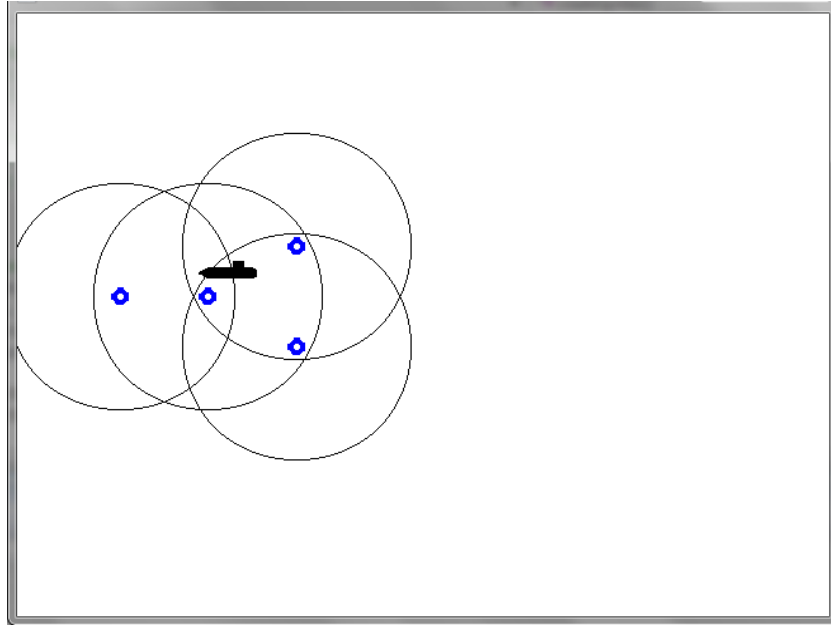


Figure 23. Initial Setup for Prototype Program

To test the geometry of the adaptive sonobuoy pattern the user is given the ability to “drive” the submarine using the arrow keys on the keyboard. There is a function to determine the number of sonobuoys whose range to the submarine is within the maximum detection range and if the result of this function drops below three to trigger a new sonobuoy to be dropped. This function will also issue a warning if the number of sonobuoys in contact with the submarine drops to less than two, which means the algorithm is not performing adequately to maintain contact with the submarine. The placement of the new sonobuoy is based on the geometry described in section 3 of this chapter.

As the submarine proceeds on an easterly course it will eventually reach a point where it will only be in range of two rightmost sonobuoys. At this point the program will direct a new sonobuoy to be dropped such that an equilateral triangle is made with the two rightmost sonobuoys as shown in Figure 24.

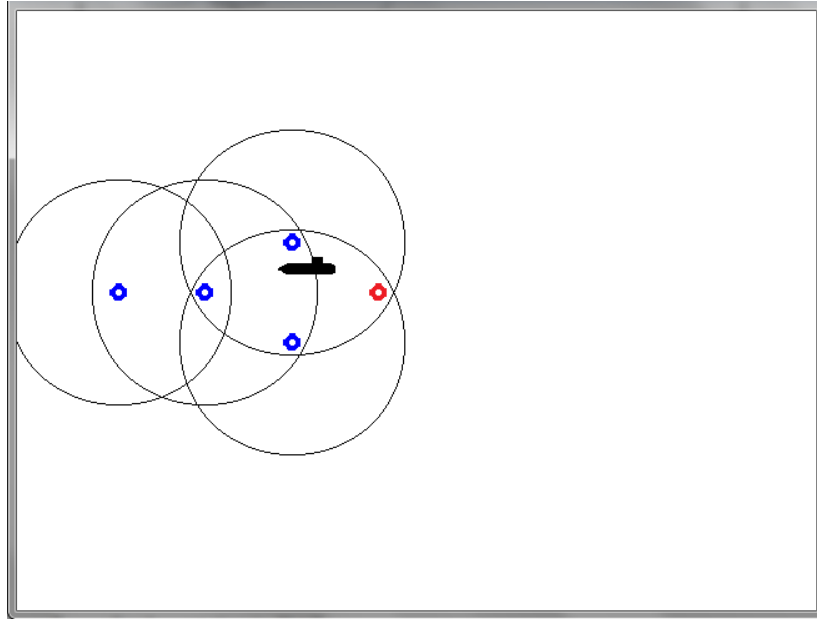


Figure 24. First Extension Sonobuoy

As the submarine continues to move forward the algorithm will continue to drop new sonobuoy (red circles) to maintain contact with the submarine. An example of the sonobuoy pattern that would develop for a submarine maneuvering is shown in Figure 25. The dotted line represents the path the submarine followed during its transit.

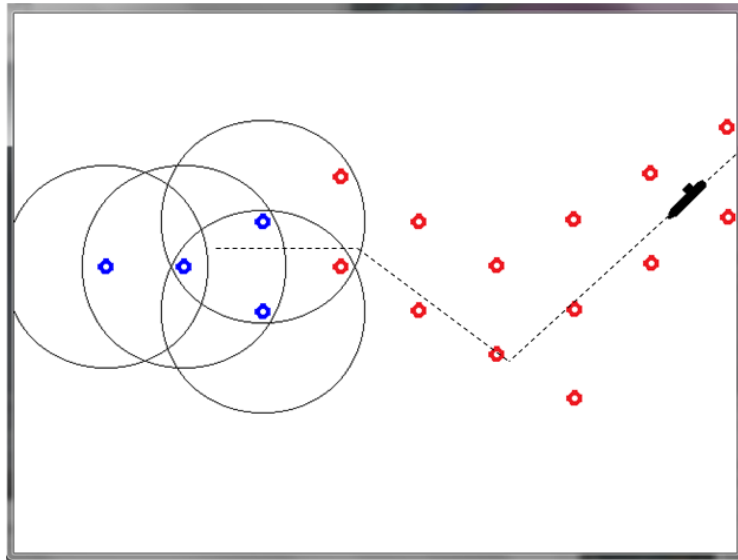


Figure 25. Extension of Sonobuoy Pattern for a Maneuvering Submarine

The prototype program was run under several conditions to test the geometry of the adaptive sonobuoy placement algorithm. The algorithm performed well and was able to maintain three sonobuoys in contact with the submarine at all times, showing that the technique of creating equilateral triangles with existing sonobuoys is an effective method for tracking a submarine in a simulation. The prototype program is based on a cookie cutter sensor model, in which the sonobuoys will detect any submarine within the radius of its maximum detection range. This does not represent actual conditions because the ocean environment varies throughout a geographic region and the sonobuoys may be less effective against a quieter submarine.

5. Implementation in JSAF

After verifying the adequacy of the equilateral triangle geometry to provide contact with the submarine, the final step is to implement the adaptive sonobuoy placement behavior in JSAF. Several more elements of the behavior have to be considered when implementing in JSAF than with the prototype program. One key difference is the fact that the JSAF environment is three dimensional and the geometry will have to work in the proper coordinate system. The actions of the P-3 will also have to be controlled to route the P-3 to the proper location for dropping a new sonobuoy at the appropriate time. Additionally, the changes to the SCCD GUI outlined in the initial behavior description will have to be implemented. After implementing the algorithm in JSAF it was tested for adequate tracking of a hostile submarine in various conditions and any deficiencies in the behavior were identified.

a. JSAF Coordinate Systems

One of the challenges of implementing the adaptive sonobuoy placement behavior in JSAF is performing three-dimensional math with multiple coordinate systems. Since using polar coordinates is a computationally inefficient and expensive way to do positional math, JSAF uses a global coordinate system (GCS) to provide locations of platforms and perform positional math (Lockheed Martin, 2012). In JSAF the earth is divided into geo-tiles called “Cells,” which are 1° by 1°. Each cell has a number

and positions are defined with X, Y, Z, cell. Each cell is a Cartesian plane tangentially placed on top of the curved earth surface and Z values are adjusted within the cell to reflect the curvature of the earth, therefore $Z = 0$ is not always sea level (Lockheed Martin, 2012).

Since sonobuoys will sink to their specified depth the Z position for sonobuoy deployment is not crucial when using GCS positions. This means the math for calculating new sonobuoy placement in GCS could be performed as a two-dimensional problem in the tangential plane for that cell. However, this does not work if the sonobuoy calculations take place at the edge of a cell and one or more of the sonobuoys are in a different cell. Therefore, the sonobuoy positions in JSAF must be converted to geocentric coordinates (GCC) before applying the geometry described in section 3. The GCC system is earth centered with coordinates based on Cartesian X, Y, and Z axes. After the new sonobuoy position is calculated in GCC, the result must then be converted back to GCS for use by JSAF. The JSAF source code contains libraries for performing vector math and coordinate conversions that are helpful in calculating new sonobuoy positions.

Another challenge regarding the coordinate systems is finding the up vector for a given location. The up vector varies over the surface of the earth when using the GCC system, but the positive Z direction gives an accurate approximation of the up vector in the GCS system. Therefore, the up vector can be found at the midpoint of the two closest sonobuoys by constructing a vector \bar{m}' at a point just above the midpoint vector \bar{m} by adding a constant to the Z component as follows:

$$m'_x = m_x$$

$$m'_y = m_y$$

$$m'_z = m_z + c$$

At this point, the up vector \bar{u} in GCS coordinates can be found by the following equation:

$$\bar{u} = \bar{m}' - \bar{m}$$

Then the up vector is converted to GCC coordinates and used in calculating the new sonobuoy position. The curvature of the earth will affect the accuracy of the up vector at the edges of cells, but it is not enough to cause a significant change in the sonobuoy pattern.

b. P-3 Routing and Timing

Another challenge with implementation of the adaptive sonobuoy placement behavior in JSAF is controlling the routing of the P-3 and dropping the new sonobuoy at the appropriate time. There already exist behaviors in JSAF that control general motion of aircraft as well as functions in the deploy sonobuoys task for creating different types of routes for deploying sonobuoys. To leverage the existing code, a new point route is created whenever a new sonobuoy is required using code similar to the calculate point route function in the deploy sonobuoys source code. The only difference is that the destination point of the route is the new sonobuoy position calculated by the algorithm vice a point designated by the JSAF operator when initiating a deploy sonobuoys task. With the route established, the existing code for routing the P-3 along the route and dropping the sonobuoy is utilized.

The timing of sonobuoy deployment is important to ensure sonobuoys are not wasted while still maintaining track of the submarine. The algorithm projects the submarine's track and finds the point along the track when the submarine will only be within the range of two sonobuoys. The goal is to have the new sonobuoy in place, at the appropriate depth, before the submarine reaches that point. Therefore, the total time for the aircraft to fly to the drop point, drop the sonobuoy and for the sonobuoy to sink to the appropriate depth must be less than the time it takes the submarine to reach the point along the track where it will lose contact.

To calculate the total time to deploy the sonobuoy there are several parameters that must be obtained from the simulation. The first part is the time to transit to the drop point, which requires the P-3's position and speed and the position of the drop point. The distance between the P-3's position and the new sonobuoy position is calculated and the transit time is simply the distance divided by the speed of the aircraft.

Next the time for the sonobuoy to drop from the aircraft and hit the water is determined based on the altitude of the P-3. Since the time for the sonobuoy to drop can vary depending on environmental conditions an approximation was made by timing the sonobuoy drop for a typical altitude for deploying sonobuoys and applying a linear interpolation such that the time to drop increases as the altitude of the aircraft increases. A similar method is used to calculate the time for the sonobuoy to sink to its ordered depth. The sonobuoys have three depth settings in JSAF, shallow, medium, and deep, corresponding to depths of 100, 400, and 1000 feet respectively. The time for a sonobuoy to sink to 400 feet was recorded and the times to reach 100 and 1000 feet were interpolated from this value to give an approximation for the time to sink. Therefore, the total deploy time is the sum of the transit time, time to drop and time to sink.

The time until the submarine reaches the point where it will only be within the range of two sonobuoys is more straightforward to calculate. The speed and position of the submarine and the position of the point along the submarine's track where a new sonobuoy will be needed are the only data needed for this calculation. The submarine transit time is found by calculating the distance between the submarine's position and the point where a new sonobuoy will be needed and dividing the distance by the speed of the submarine. To ensure the new sonobuoy will be ready ahead of time the submarine transit time is reduced by a lead factor of one minute. After the times are calculated, they are compared and as soon as the total deploy time is less than or equal to the submarine transit time the algorithm directs the P-3 to commence its transit to drop a new sonobuoy.

c. Graphical User Interface Changes

Several changes to the GUI for the SCCD are necessary for implementing the adaptive sonobuoy placement algorithm. A checkbox to allow the operator to choose if automatic tracking of a submarine is desired should be added to the Deploy Sonobuoys task menu as shown in Figure 20. Also, an alert icon and accompanying alert message for the P-3 should be added to alert the operator to a loss of contact with the submarine since manual control of the P-3 will be required. Finally the route overlay of the P-3 will have

to be updated to delete the existing route and show the new deployment route to minimize clutter on the map display and show the operator the intended actions of the aircraft.

Due to time constraints, the addition of the checkbox to the Deploy Sonobuoys task menu and the alert icon and message were not implemented in the initial behavior development. The implementation of the changes to the overlay was completed by leveraging existing source code in JSAF. To delete the overlay for the current sonobuoy field being deployed the vehicle movement order is deleted as soon as the P-3 is directed to track a hostile submarine. The overlay for the new route is already programmed as part of the create point route function so as soon as the new route is ordered the new overlay of the P-3's route is displayed. The different route overlays can be seen in Figure 26 as the yellow dotted line with the arrow at the end of the route.

The GUI changes not instantiated require changes to a separate code library than the deploy sonobuoys library, which is beyond the scope of this research for developing new behaviors. Additionally, these changes will not have a significant impact on the effectiveness of the adaptive sonobuoy placement behavior if not initially implemented.

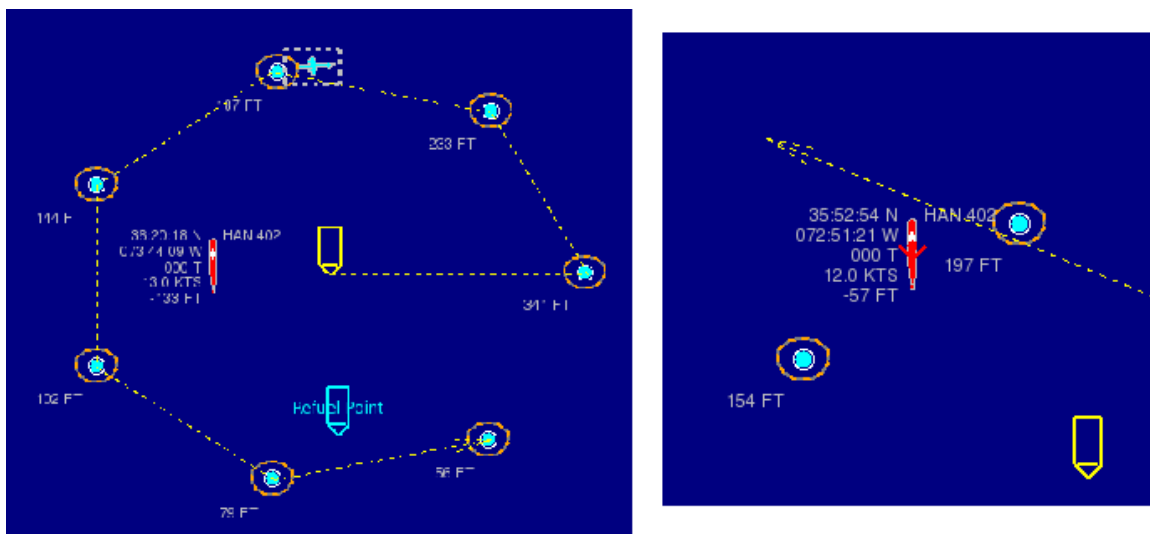


Figure 26. Route Overlays for Initial Pattern (Left) and New Sonobuoy (Right)

d. Testing the Implementation in JSAF

After overcoming the challenges outlined in the preceding sections, the adaptive sonobuoy placement behavior was programmed into the JSAF source code as part of the deploy sonobuoys behavior library. During the implementation and at completion of the algorithm several checks and tests were performed to verify the accuracy and adequacy of the behavior.

In the early stages of development of the behavior small pieces of the algorithm were verified. First the geometry was verified by calculating the distance between the positions of the three sonobuoys to ensure they were equal as well as measuring the distance on the map display with the “Measure Distance” tool to ensure the curvature of the earth did not have a significant effect on the shape of the pattern. It was also necessary to ensure the algorithm was properly picking the two closest sonobuoys as well as dropping the new sonobuoy on the correct side of the two closest sonobuoys based on the submarine’s course. Next, the projection of the submarine’s track was verified along with the timing for dropping a new sonobuoy before contact was lost with the submarine.

After these building blocks were verified several scenarios were run to test the ability to track a hostile submarine as it maneuvered. The adaptive sonobuoy behavior allowed the P-3 to automatically maintain track on a submarine in several cases of submarine maneuvers including changes in course, depth, and speed. Due to the fact that the detailed environmental model was not loaded on the JSAF workstations at the Naval Postgraduate School, testing of the behavior in varying underwater environmental conditions was not conducted.

Some gaps in the behavior that were not addressed in the initial scoping of the algorithm were discovered during testing. In some cases, if the P-3 was required to make a sharp turn to drop a new sonobuoy it would drop a sonobuoy in the wrong position and the cause of this behavior has not been identified. There are also cases where the P-3 would lose contact with the submarine and continue to transit away from the area of the sonobuoy field. The algorithm did not address procedures for loss of contact with

the submarine, but the P-3 should at least orbit the location of the sonobuoy field to allow the operator to take control of the P-3 and try to regain contact. The last deficiency noted with the algorithm was the way it handled gaining contact on a submarine when it was outside of the normal range of the sonobuoy field and heading towards the sonobuoy field. In this case it would drop a new sonobuoy in the same place repeatedly until the submarine entered the detection range of the sonobuoy field. This behavior wastes sonobuoys and does not place sonobuoys in the ideal location in this case, however, it is unlikely to gain contact on a submarine outside of the detection range of the sonobuoy field unless it was detected visually or by radar. If this was to occur, the operator would need to take manual control of the P-3 to track the submarine.

Overall, the adaptive sonobuoy placement behavior was successfully implemented in JSAF by modifying the existing deploy sonobuoys behavior. There are limitations to the initial behavior developed with this research effort, which are noted above and in the initial statement of the scope of the algorithm. The source code and operation of the behavior was reviewed by personnel at NWDC and they believe the work done on the algorithm thus far could be easily built upon and that it would benefit the JSAF operators responsible for controlling P-3s.

A small test was performed to provide a preliminary check of the usefulness of the adaptive sonobuoy placement behavior in reducing the workload of JSAF operators. This is by no means a full experiment of actual operators performing their jobs during a FST exercise, but it does show positive results. A small scenario was setup in the local version of JSAF to track a submarine as it transited and performed maneuvers. The scenario was initiated with the submarine starting a transit with two changes in course and a P-3 in the vicinity with intelligence about the submarine's location. The scenario was run with the automated behavior disabled and then with the behavior enabled for one hour to determine the number of mouse clicks required by the operator for each case. The operator's tasking was to deploy an initial sonobuoy field and continue tracking the submarine by extending the pattern with additional sonobuoys.

The test of the adaptive sonobuoy placement behavior showed a marked reduction in mouse clicks required when the behavior was enabled and allowed the P-3 to

maintain contact with the submarine. With the behavior disabled, the JSAP operator deployed six sonobuoys after the initial sonobuoy pattern was deployed and the submarine was detected. In the scenario with the behavior enabled the P-3 automatically deployed seven additional sonobuoys due to dropping a sonobuoy where the human operator would have opted to save a sonobuoy. In both cases, 13 mouse clicks were required to deploy the initial sonobuoy field, check the submarine contact information and pan/zoom the map display. For the case with the behavior disabled, seven mouse clicks were required for each additional sonobuoy deployed for a total of 42 additional mouse clicks. No additional mouse clicks were required to deploy the additional sonobuoys when the behavior was enabled. Therefore, the total mouse clicks required with the behavior disabled was 55, compared to just 13 with the behavior enabled, which gives a 76 percent reduction in the number of mouse clicks required to control one P-3 for a one hour period. The test of the behavior shows that there are tangible benefits to automating platform behaviors in JSAP, but further testing is required to determine if the number of simulation operators can be feasibly reduced.

V. CONCLUSIONS

A. CONCLUSIONS

This thesis has successfully demonstrated and documented a methodology for creating automated behaviors for Multi-Mission Aircraft in JSAF, which can help reduce the workload of JSAF operators. This will ultimately help with the budget constraints at NWDC by allowing fewer operators to control the same number of entities or by allowing more entities to be controlled by the same number of operators. The methodology presented can easily be extended to further automate P-3 behaviors and to create behaviors for other platforms.

The first part of the research was to evaluate the way JSAF operators control the simulation of P-3s for FST exercises. This consisted of conducting a literature review of relevant topics, speaking with SMEs and observing operators during an actual exercise. Several behaviors that could be automated were identified including conducting a torpedo attack on a submarine, deploying sonobuoys to track a submarine, and plotting overlays for operating areas. It was decided that adaptively deploying sonobuoys to track a submarine is the best behavior to automate.

The next part was to determine the best method for implementing the behavior in JSAF. The benefits and drawbacks of three different methods were considered for implementation. Direct manipulation of the JSAF source code was chosen over the Discovery Machine approach or using an external program with an interface to JSAF. This method was chosen because the code for the behavior would be owned by NWDC and could be more easily incorporated into JSAF and adapted to represent actual classified ASW tactics.

The final portion of the research was to implement the adaptive sonobuoy placement behavior in JSAF. This involved describing and scoping the behavior, testing the geometry of the sonobuoy pattern using a prototype program, and programming the behavior in JSAF by manipulating the deploy sonobuoys behavior. The result at this stage

of the research is a modification of the deploy sonobuoys behavior in JSAF that causes a P-3 to automatically track a hostile submarine by deploying sonobuoys along its track.

The adaptive sonobuoy placement behavior is limited in scope to tracking only one submarine at a time, in an open-ocean environment, with no other air assets in the area. The behavior does not represent actual ASW tactics, but does a reasonable job of maintaining track of a submarine as it changes course, speed and depth. The algorithm does not account for situations where the P-3 runs out of sonobuoys or for changes in the acoustic environment that may require different sonobuoy spacing, depth settings, buoy life settings, or the use of active sonobuoys.

The adaptive sonobuoy placement behavior implemented in JSAF has shown promise for reducing the workload of JSAF operators. In a small scenario, the adaptive sonobuoy behavior allowed for a 76 percent reduction in the number of mouse clicks required to control a P-3 over a 50 minute period. This would allow the JSAF operator to concentrate on the tasks for other P-3s such as rerouting or conducting torpedo attacks on other submarines. This could allow a single operator to effectively control more P-3s simultaneously and reduce the total number of operators required for a given exercise.

B. FUTURE RESEARCH

Since this research is an initial effort to describe a methodology for automating behaviors in JSAF there is a large amount of future work that can be accomplished to allow a reduction in the number of JSAF operators required to run a FST exercise. The future work for this thesis can be separated into two distinct categories. One category involves fully developing the adaptive sonobuoy placement behavior, and the other category is for future work to automate other P-3 behaviors as well as behaviors for other platforms and testing the effect of the automation on the workload of JSAF operators.

The first step towards getting the adaptive sonobuoy placement behavior fully implemented in JSAF is to properly separate the behavior from the deploy sonobuoys behavior that already exists in JSAF for dropping a set pattern of sonobuoys. The proper method for accomplishing this is to create a separate background task that checks for a hostile submarine detection by the P-3, and having the background task trigger a separate

reactive task, which will commence dropping sonobuoys to actively track the submarine. The reactive task would take priority over the existing deploy sonobuoys task, but would allow the deploy sonobuoys task to resume if contact with the submarine was lost. Once the tasks are properly separated, the tracking behavior can be further developed to account for all possible situations, incorporate classified tactics and fix any deficiencies in the behavior.

The initial description and implementation of the adaptive sonobuoy placement behavior was limited in scope, based on unclassified methods for tracking a submarine and exhibited some erratic behaviors in some instances. Before including the adaptive sonobuoy placement behavior in an official update of JSAF, all of these issues will have to be addressed. The scope of the algorithm will have to be expanded to handle multiple submarines and/or MMA assets in the same geographic area, operations in littoral regions, and actions for low sonobuoy counts, changes in the acoustic environment and loss of contact with the submarine. The behavior will also have to be modified such that the P-3 will realistically take actions according to approved ASW tactics and procedures, which should primarily consist of altering the geometry of the sonobuoy patterns. Additionally, the erratic behaviors of the P-3 dropping the sonobuoy in the wrong place when making sharp turns and dropping several sonobuoys in the same location if the submarine is approaching the sonobuoy field from long range will have to be corrected. After these corrections are made, the final touches to the GUI of adding a “track submarine” checkbox and a loss of contact alert icon and message must be implemented. If these updates are made, the adaptive sonobuoy placement behavior could be incorporated into JSAF for use during FST events.

The adaptive sonobuoy placement behavior, even when fully implemented in JSAF, only provides a partial solution to reducing the workload on JSAF simulation operators. There are still other behaviors that can be automated for MMA platforms and there are other platforms that can use increased automation. Once these behaviors are identified, a study should be completed to evaluate which behaviors will provide the greatest return with the least amount of effort to implement in JSAF.

The small test of the adaptive sonobuoy placement behavior is only an example of how the effectiveness of new platform behaviors can be evaluated. More thorough experiments should be conducted to determine the effects of behavior automation on the ability of simulation operators to provide accurate and timely simulation of several entities or platforms simultaneously. Experiments could be conducted with simulation operators during actual FST events or while operating a standalone station with a fixed scenario. There is also a variety of dependent variables and that can be measured using methods beyond simply recording the number of mouse clicks. For example, eye tracking software could be used to measure the time an operator has to concentrate on a given task. Additionally, surveys or questionnaires can be used to gauge the satisfaction of the JSAF operators with the automated behaviors. There are many ways to test the effectiveness of automated behaviors, but it is important to conduct testing to ensure automation efforts are not wasted.

There were additional tasks or behaviors identified by this study that could be automated to help reduce the workload of JSAF operators. For the P-3s, the automation of torpedo attacks on submarines is the best candidate for further automation. Automation of creating overlays for operating areas based on tasking messages in JSAF could benefit several platforms besides MMAs and could facilitate smoother operations during complex exercises. Additionally, behaviors similar in nature to the adaptive sonobuoy placement behavior could be implemented for other platforms, such as automatic tracking of a submarine by another submarine or by a surface ship. Further automation of tasks could simplify the duties of JSAF operators such that they are primarily responsible for monitoring the platforms under their cognizance and making proper reports to the LNOs. Automation of behaviors can also provide consistent and realistic behaviors for entities regardless of the experience level of the JSAF operators.

C. RECOMMENDATIONS

Several issues with the conduct of exercises were noted during the observation of TEMINAL FURY. The training level of the JSAF operators was inadequate, therefore, it is recommended to have a short training session on the operation of the SCCD and

simulation of platform specific tactics in JSAF before commencing a major exercise. It may also be useful to have a condensed guide or tutorial of the SCCD and common tactics for quick reference by the operators when they are busy controlling multiple platforms.

Another area that could use improvement is organization and coordination amongst the simulation team during exercises. Coordination can be improved by assigning platforms to operators by geographic area or mission type, which helps the operator focus on a limited scope of operations and helps team organization. Another area of organization that needs improvement is the tracking of mission timing by JSAF operators. The operators use their mission assignment papers to keep track of the times for the next mission event (take off, return to base etc.), with the papers in a pile in no apparent order. A timeline program with a row for each mission and the event times annotated would alleviate the possibility of operators being late to complete events.

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